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A study and survey of the use of finite element models of aircraft structures in the Air Force has been conducted. The results show that the Air Force is not getting full value for the resources that are invested in models, both directly and by contractors. Contractors are not required to deliver the models they create to the Air Force. When the Air Force needs these models, they must either be procured from contractors, re-created, or forgone. Models that are available are often documented inadequately, or not at all. A centralized Air Force activity is proposed, in which models are acquired, documented, verified, exercised, modified, publicized, and disseminated. Database software has been identified for use in this Center. Also, a Mil-Standard is proposed that could be used for future model delivery requirements. A Phase II effort is proposed in which the ideas developed in Phase I would be expanded and excerised in anticipation of future permanent establishment of the Center.

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This report documents a feasibility study for a program that would acquire, validate, modify, store, retrieve, and disseminate finite element models of Air Force aircraft structures, along with associated documentation. The study also addresses standards for delivery by contractors of finite element models of future systems developed for the Air Force. The work was performed by CSA Engineering, Inc. and its subcontractors, Aerospace Structures, Inc., and Applied Technology, Inc., under contract F33615-87-C-3231.

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Gordon R. Negaard (Aerospace Structures, Inc.): Sections 3, 4, 6, 9, 10, and 11.

Michael R. James (ATA): Sections 3 and 7.

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FINITE ELEMENT MODELS FOR THE SUPPORTABILITY OF UNITED STATES AIR FORCE AIRCRAFT STRUCTURES

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This report is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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1. Introduction and Executive Summary

1.1 The Promise of Finite Element Analysis

The finite element method has become a standard for design analysis of aerospace structures. It is an irreplaceable tool for all aerospace organizations, and for the Air Force itself. While emphasis has shifted somewhat toward commercial software packages, most aerospace firms also devote significant resources to in-house finite element software development, evaluation, and training. Finite element analysis promises faster and more accurate analysis, more efficient designs, and less dependence on costly and time-consuming tests.

1.2 The Promise Unfulfilled

The prevalence of finite element analysis in many industries is testimony to its effectiveness. Yet in some ways the promise of the method remains unfulfilled. Considerable resources are devoted to finite element models, and the return on these resources is not what it should be. Many models die a premature death because they were not adequately documented, verified, publicized, or made available to organizations that could have made use of them.

Within the Air Force, this problem was perceived by Dr. V. B. Venkayya, Dr. James Olsen, and others in the Structures Division of the Flight Dynamics Laboratory who have been leaders in developing methods of structural analysis and optimization for many years. Briefly, the problem is that the Air Force is getting nowhere near full value for the finite element models that are developed either directly or by contractors. Generally speaking, contractors are not required to deliver the models they develop as a part of their structural design analysis work. There are many circumstances in which the Air Force could benefit from having these models after the aircraft have been put into service. When such circumstances arise, Air Force personnel have no good choices. They either develop models themselves (labor-intensive), pay a contractor to develop a model (expensive and difficult to fund), or do without (losing valuable opportunities).

The idea behind this SBIR program is that these problems might be remedied by establishment of a centralized operation dedicated to identifying, collecting, documenting, verifying, storing, modifying, and disseminating finite element models of Air Force aircraft. In addition, a specification is proposed that could be used for future procurement programs so that contractors were required to deliver models to the Air Force. The specification would primarily address documentation and format requirements.

1.3 Goals

The Phase I feasibility study was intended to do the following:

1. Evaluate current practices in finite element analysis among selected Air Force organizations.
2. Outline a military standard that could eventually be used to specify requirements for delivery of finite element models by aircraft development contractors to the Air Force.
3. Propose a plan of operation for an Air Force center where models would be collected, documented, verified, modified, stored, retrieved, and distributed, with emphasis on potential cost savings.
4. Investigate supporting software that could be used in the operation of this Center.

Phase II will form a pilot operation with attention focused on models of a particular aircraft. Following Phase II, full operation of a Center is contemplated.

1.4 Findings

The findings of this study may be summarized briefly as follows:

1.4.1 Survey Confirms FDL Suspicions

The Air Force is not getting full benefit from the finite element models of aircraft structures that are developed by contractors. The perceptions of FDL engineers and others that this is so are supported by the survey reported in Section 3 and by the authors' personal experience. This is partly a management problem and partly a technical problem. That is, there are few if any organized procedures for acquiring, documenting, modifying, and distributing these models. This report shows that these problems are costing the Air Force a lot of money and many lost opportunities.

1.4.2 Lack of Model Delivery Requirements: the Consequences

Contractors are not currently required to deliver the finite element models they develop while designing aircraft. Our survey showed several cases where Air Force organizations needed models that perhaps should have been delivered when the aircraft were procured. In these cases they either paid for another model to be created, or did without. There have probably been many cases where Air Force organizations recognized a need for a model but immediately dismissed the idea,

believing that the obstacles to finding or creating the model they needed were too great.

1.4.3 Mil-Standard Needed

It will not be sufficient to simply insert a new CDRL item in future contracts to require delivery of models. A standard is necessary to specify the format of the data, and the form and content of supporting documentation. An outline for such as standard is presented in Section 6 of this report.

1.4.4 Documentation is Crucial

The importance of documentation supporting finite element models is difficult to overstate, no matter where the models come from. Undocumented raw data can be very difficult (even dangerous) to use. Documentation is especially important when several variations of a basic model exist, as shown in the case study described in Section 4. Another case study, showing well-documented models, appears in Section 5.

1.5 Recommendations

The recommendations presented in this report are based partly on the survey results and partly on the personal experience of three of the engineers who worked on it. This experience amounts to about forty years among the three of them doing finite element analysis. The recommendations are as follows:

1.5.1 Air Force Aircraft Model Center Proposed

A centralized activity is proposed for supporting finite element models of Air Force aircraft. This activity is tentatively called the *Air Force Aircraft Model Center.* The Center would be responsible for acquiring, validating, documenting, modifying, distributing, and publicizing finite element models of Air Force structures. The following payoffs are envisioned:

1. Costs incurred in acquiring or developing models would be avoided in cases where the Center can supply an existing model to an Air Force organization. Costs are discussed in Sections 3 and 4 and in the Appendix.
2. Dramatic benefits can be foreseen in situations where a change in an aircraft's structure, loads, or mission requires quick evaluation of stresses or other structural responses. If no model is available, quick response is impossible. If the Center can provide a well-documented model, ready for use (or nearly so), the

cost savings and additional benefits could propagate widely through the Air Force.

3. Researchers and developers will have at their disposal a library of models that they can use to validate new technology such as optimization or multidisciplinary analysis.

1.5.2 Mil-Standard Outlined

An outline of a proposed Mil-Standard for finite element models is developed in Section 6. Its aim is to insure that developers of future aircraft systems will deliver models to the Air Force according to certain standards. The standards address matters such as documentation, verification, and format.

1.5.3 Database Software Identified

A specific database solution has been identified that addresses the problems of identification, storage, and documentation of models. It also provides automatic tracking of updates and variations, along with documentation keyed to the actual bulk data. The software will provide menu-driven search and retrieval functions tailored to the needs of structural analysts. The software is spelled out in detail in Section 7.

1.5.4 Phase II Plan Developed, Permanent Operation Foreseen

A plan has been developed for Phase II in which the ideas identified in Phase I will be exercised on live data. This plan is discussed in Section 10, with more detail presented in the actual Phase II proposal. The goal of Phase II is to accumulate the experience, software, etc., necessary for operating the envisioned Center. Center operation is discussed in Section 11.

2. Statement of the Problem

With each new Air Force aircraft system that has been developed, finite element analysis (FEA) has played a greater role in the structural design analysis process. Older aircraft such as the B-52 that were designed entirely by hand have also been the subject of finite element analysis in recent years. Certainly FEA is now irreplaceable in aircraft structural design and analysis. However, as Drs. Venkayya and Olsen point out in their recent paper (Ref. [3]), the Air Force is not getting full value for the resources that are spent either directly or by contractors on FEA.

Before defining the problem in more detail, it will be useful to review the evolution of finite element analysis, and to summarize the current state of affairs in this field.

2.1 Evolution of Finite Element Analysis

The finite element method evolved in parallel with the rise of digital computers. Because of intensive matrix computations, a computer is necessary for even the simplest models. Twenty years ago, FEA was much different than it is today. NASTRAN had not yet appeared, and most organizations supported their own in-house codes. Card decks were standard, and a big model had a thousand degrees of freedom. Pen plotters were the state of the art in graphics.

At first, attention was naturally focused on basic methods: issues like element formulations and equation solution methods. Later, software reliability and expanded problem sizes were addressed. In recent years, considerable effort has been expended on graphical pre- and post-processors. Perhaps the present effort will turn out to be part of another shift in focus in the industry, this time toward protecting investments in models by organized efforts to verify, document, preserve, and disseminate these models.

2.2 Costs of Finite Element Analysis

The costs of developing a finite element model can be staggering. One of the engineers whom we contacted in our survey (Section A.1) quoted a cost of $500,000 for development of a model they wanted. While this was an off-the-cuff remark, it probably reflects the order of magnitude of the costs that can be incurred in modeling.

There are three major components of the overall cost:

1. Computer hardware.
2. Computer software.

3. Engineering manpower.

It is common knowledge that the hardware cost of performing a unit of computation has dropped spectacularly in recent years. But demand has kept pace with the falling unit costs so that hardware expenditures have fallen only slightly in absolute terms; perhaps more in percentage terms. However, these costs can still be substantial. In large organizations, finite element analysis tasks can consume much of the power of a multi-million dollar supercomputer.

Engineering software effectiveness has increased more slowly, but again demand has more than offset gains here.

Engineering manpower productivity has increased most slowly. Most of the manpower productivity gains have come about with the introduction of graphics pre- and post-processing software. In both absolute and percentage terms, manpower costs in FEA have risen substantially.

Thus manpower is certainly the most important consideration in FEA costs. Two keys to controlling manpower costs are (1) to be sure that expensive engineers are working on the right problem, and (2) that they are not duplicating someone else's work. This is where dissemination and documentation play a key role. Clearly, if an Air Force organization can acquire the right model rather than reinvent it, considerable time and funds will be saved. If the model is properly documented, engineers will be sure of what they are working on.

2.3 Air Force Needs for Finite Element Models

All developers of Air Force aircraft use finite element analysis in the structural design process. Considerable resources (computer hardware and software costs; engineering manpower) are devoted to the development, verification, and use of these models. These resources are all provided, at least indirectly, by the government, and so it would seem that these models ought to belong to the government. However, contractors only deliver what their contract requires them to deliver.

There are many reasons why Air Force organizations such as ASD, AFLC, and AFWAL might need such models, such as

- Providing support for repair and maintenance operations,
- Investigating new versions of aircraft (e.g., F15A – F15E),
- Investigating modifications to existing aircraft (new weapons systems, performance enhancements, etc.),
- Validation of contractors' analyses, and

- Provision of realistic test problems for validation of new technology. New capabilities added to the ASTROS software, for example, need to be evaluated on realistic problems. Models of existing systems are ideal for this purpose.

Since there has been no requirement for delivery of models in past system developments, models have been obtained under less than satisfactory conditions, if at all:

- Models have been acquired from the developers through informal requests, usually with little or no supporting documentation,
- Models are sometimes purchased (twice, in effect) from the original system developers,
- Contracts are sometimes let to third parties to create new models.

The Air Force does not have the manpower to devote to creating complex models, so until now, these three approaches have been the only means of obtaining the required models.

Getting contractors to deliver models means more than just another item added to a CDRL. It will be necessary to provide specific requirements regarding documentation, verification, and data formats. This subject is addressed in some detail in Section 6. This specification expands on the ideas presented by Dr. Venkayya in his DID (Ref. [2]) and in his conference paper (Ref. [3]).

2.4 Need for Documentation

The authors know from personal experience the importance of documentation of finite element models. This becomes dramatically apparent to an analyst who is given an undocumented model and asked to make modifications. In the worst case, without even any comments in the bulk data, the analyst must begin a laborious process of plotting and running the model. Plots are necessary to find out node point and element locations, and to relate element properties and material types to specific areas of the structure. Test runs must be made to validate the model for statics and dynamics.

Documentation issues are addressed in Section 6, which outlines requirements for delivery and documentation of models, and in Section 7 which proposes database software that would not only preserve existing documentation and make it accessible, but also encourage users to provide additional documentation.

3. A Survey of Finite Element Users

Six Air Force organizations and one NASA organization involved in structural analysis were surveyed during the course of this effort. Some of them were interviewed in person, others by telephone. The main purpose of the surveys was to gauge the need for a Center as contemplated in this SBIR. The respondents were asked about their use of finite element models, particularly how they acquired them, verified them, and used them. Another purpose was to ask them if they thought that a Center such as we propose would be useful to them.

The following organizations were surveyed: ASD/ENFS (WPAFB), Eglin AFB, 4950th Test Wing (WPAFB), Warner-Robbins ALC, Hill AFB, Sacramento ALC (McClellan AFB), and NASA/Dryden. Transcripts of each interview appear in the Appendix.

All six Air Force organizations are definitely involved in structural analysis and would be potential users of or contributors to the proposed Center. While some are more active than others in creating or using models, all are heavily dependent on contractors to supply them with models. More to the point, they nearly always depend on the contractor's assurance that the model is valid. Clearly, all these organizations would benefit from better procedures for delivering, documenting, and verifying models.

All the organizations surveyed have access to DEC VAX computers. Most of them also access Cray or Cyber mainframes.

All six organizations use NASTRAN, although Sac ALC prefers to use GIFTS whenever possible. The two organizations at WPAFB (ASD and 4950th) use COSMIC NASTRAN (although 4950th also has access to MSC/NASTRAN through a commercial computing network). The other four use MSC/NASTRAN exclusively. This situation generally reflects the predominance of NASTRAN in industry. There is a wide variation in pre- and post-processing software, however. Among the six organizations, two use PATRAN, one SUPERTAB, one GIFTS, one is getting NAVGRAF, and one did not report any graphics software.

Following were some of the more interesting responses, paraphrased:

> "When you have to go to the contractor for a model, it's going to take a year or more, so if something has to be done in a timely manner, it just doesn't get done."

> "Only contractors understand models, to any real degree."

> "We spent $50,000 to obtain a model. The model was actually 'free'; the documentation cost $50,000. Creating the model would have cost $500,000."

"How do we validate models? As best we can!"

"Use of COSMIC NASTRAN instead of MSC/NASTRAN would be a 'kiss of death' for the Center."

Responses to the idea of a Model Center varied widely. Hill was "very receptive," saying the Center could help "a lot." ASD and the 4950th favored it, ASD implying that the Center might make it possible to undertake some structural analysis projects that would otherwise be impossible. Warner-Robbins had moderate interest with reservations, Sac ALC was negative, and Eglin had no opinion.

We do not claim that this semi-formal survey of seven organizations is comprehensive. We do believe that it supports the conclusion that there is a need for and a cautious interest in a Model Center. Reading between the lines, we would say that most of the organizations are willing to be shown that the Center would benefit them. Thus, the manner in which the Center is presented to potential user organizations will be crucial. People become comfortable in their ways of doing their job, and are often resentful of outsiders whom they perceive as intruding, interfering, or threatening their position. This what we inferred from the response received from Sac ALC. Thus it will be very important that results can be shown at the end of Phase II which can be shown to benefit other Air Force organizations. That is, we should be able to go into one of these organizations and say, "Here's what we've accomplished in our trial operation of the Model Center, and here's how it could benefit your organization in the future." It will be important to address this presentation to the proper levels of management, not just the workers who deal with models. This is because the benefits of the Center need to be understood in terms of organizational mission performance and costs.

4. F-16 Case Study: Consequences of Poor Documentation

Some of the difficulties and frustrations experienced in working with a model obtained with little or no documentation can be illustrated with the following case study which was performed for FDL.

4.1 Evaluating the Finite Element Models

A finite element analysis was requested to quantify and evaluate the effects of real damage caused by live firings on an F-16 wing. Two finite element models were located and obtained. One model was an MSC/NASTRAN model freshly obtained from General Dynamics. This model was very extensive, containing over 7,000 grid points and an immense amount of structural detail. The other model had been around the Flight Dynamics Laboratory for several years, so long that its origin had been forgotten. This model contained around 400 grid points and over 1,000 elements. Plots of the two models may be seen in Figures 1 and 2. Note that the coarse model shown includes some elements within the fuselage, presumably for modeling the wing root stiffness.

Neither model had any documentation, so it was necessary to run the models, obtain plots, and study the results in order to gain an understanding of each model, its structure, constraints, and materials. The larger model had to be converted to COSMIC NASTRAN and then debugged before it could be run. All this preliminary work used up considerable engineering manpower and computer time without producing any directly applicable results.

It would have been desirable to use the more detailed model, but the required time and manpower would have been excessive. This was partly because so much of the budget was consumed in preliminary activities. It therefore seemed necessary to use the coarse model. From the preliminary work, the coarse model appeared acceptable, since it seemed to represent a fully configured wing. But before it could be used with confidence, it had to be validated in some way.

4.2 Verifying the Coarse Model

When the same static load was applied to each model the predicted deflections were very similar. This gave evidence that the two models had essentially the same bending stiffness. However, when computed deflections were compared to measured deflections obtained from a test having ostensibly the same loads, the results disagreed by over 100 per cent. This was found to be due to flexibility in the test fixture jig at the wing root. It should have been possible to introduce flexibility

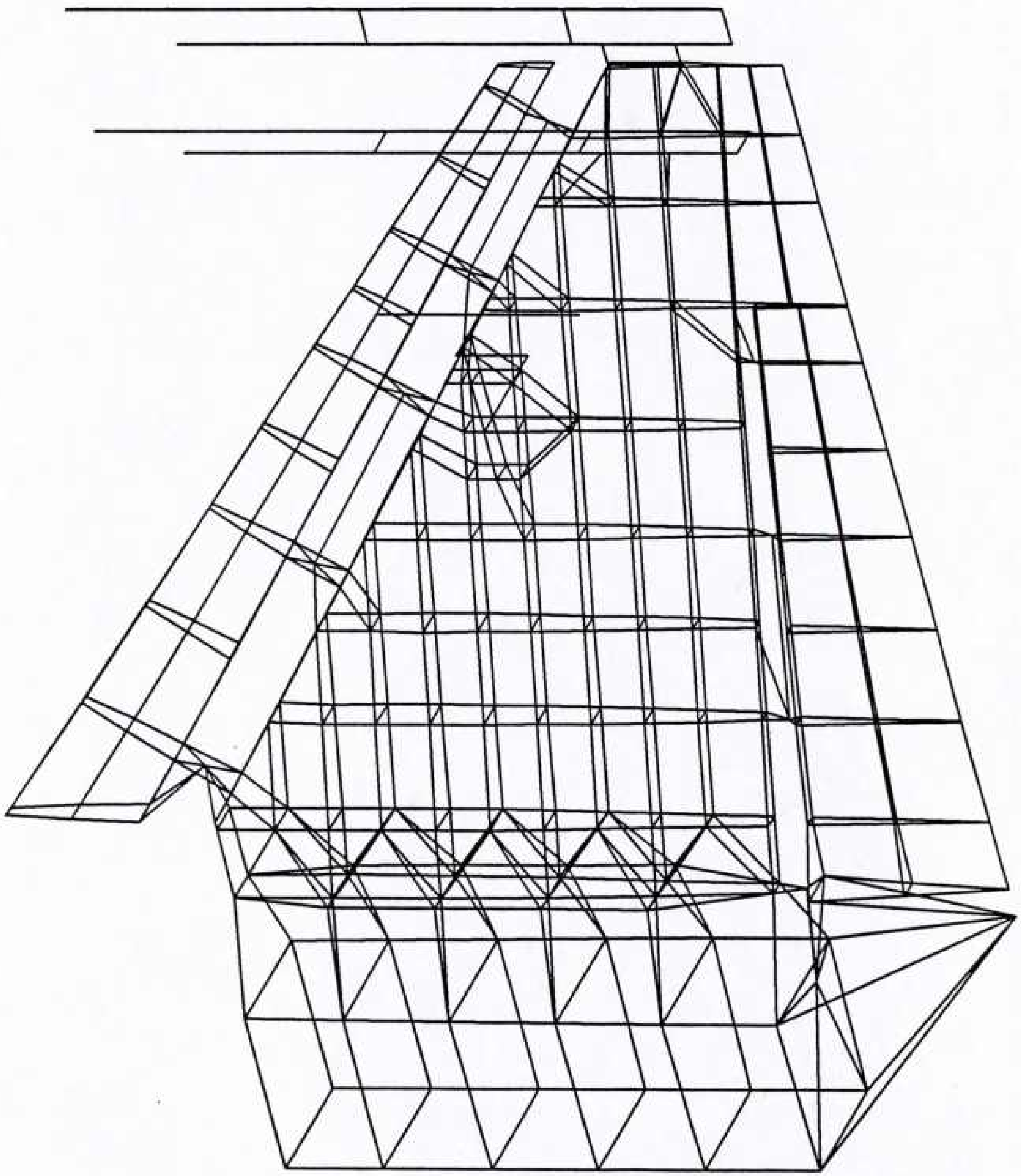

Figure 1. F16 coarse model

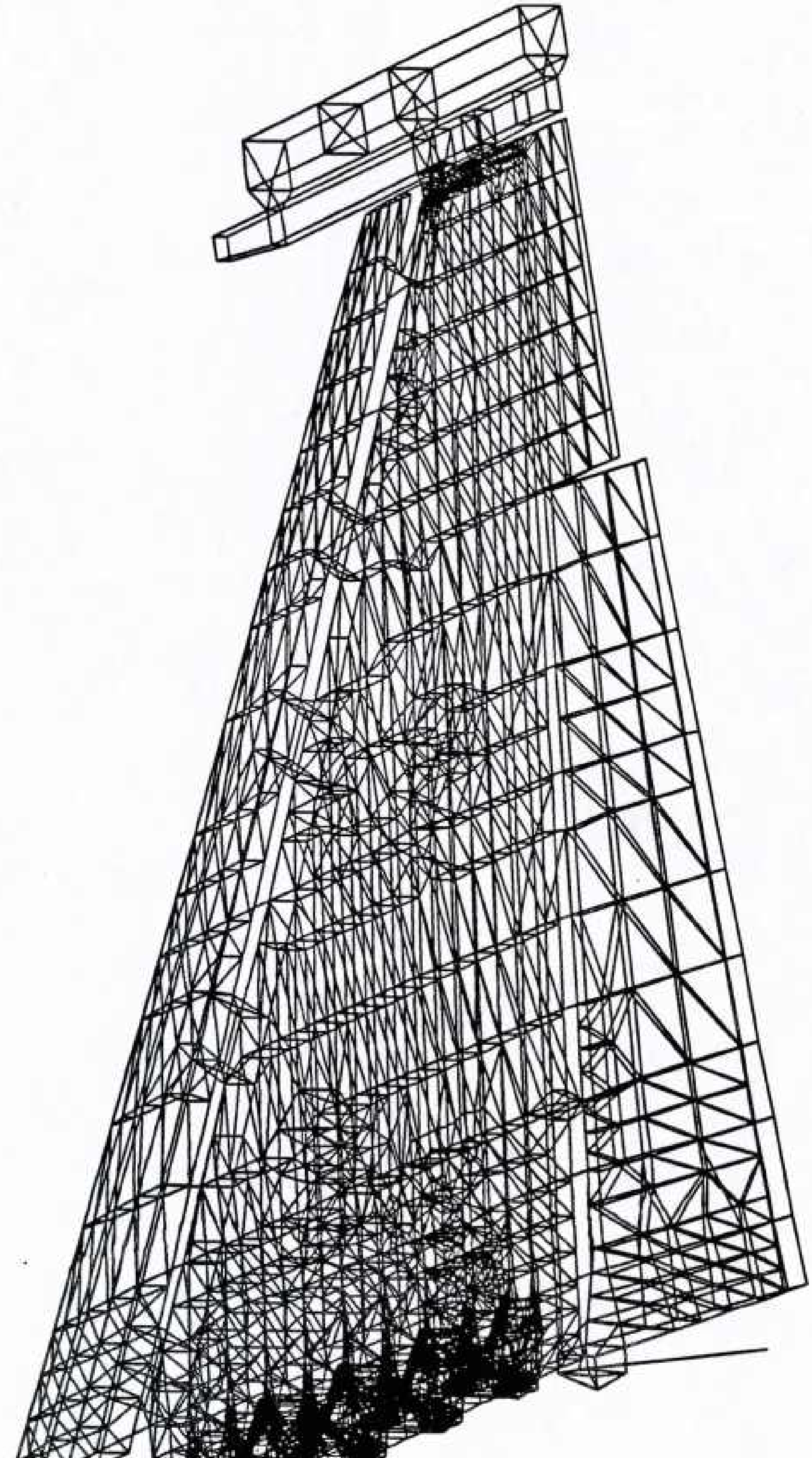

Figure 2. F16 fine model

into the root area of the wing model so that predicted deflections could be made to match the test results. Again, time and manpower constraints did not allow this. It appeared that a comparison of dynamic results would be easier, and this was undertaken instead.

First, the fully configured FDL finite element model was compared to the results of an FDL ground vibration test on a similarly configured wing on an actual aircraft. The first two natural modes matched quite well.

The next step was to compare the model to vibration tests of the test wing, since these tests would be conducted several times between firings in order to evaluate changes in the dynamics of the wing. Since the test wing was stripped of all external structure, it was necessary to remove all items such as the front and rear flaps, missiles, and pylons from the model. This was a time-consuming task due to the lack of documentation. The predicted weight was still about 200 pounds greater than the measured weight, so it was necessary to remove a percentage of the non-structural mass included in the model. After the weight had been adjusted to within a few pounds, the first four natural modes predicted by the model matched the vibration tests within a few per cent.

This correlation was considered close enough to proceed with the damage study. Each damage case was modeled and static and dynamic characteristics were tabulated before and after each shot in order to assess residual strength degradation due to the damage. Ten damage cases were analyzed for the study. Since the test wing was repaired after each test, these repairs also had to be modeled.

4.3 Cataloging the Models

Ten damage cases with two models each resulted in twenty configurations, along with four configurations of the undamaged model. (Three test wings were used for the tests, each varying slightly in configuration and weight, depending on the structure removed.) A dynamic and a static analysis was made with each model. As a result, there were 48 NASTRAN decks in use. The differences between decks varied from a few dozen cards to a few hundred. Bookkeeping became very important in keeping track of each model and in preventing errors from propagating.

For similar analyses done in the early 1970's, the CDC UPDATE utility was used (see Section 7). The original model was kept on permanent file, and a separate update deck in punched card format was kept for each case. These decks could be marked and written on in order to keep them straight.

For the F-16 study, complete decks were kept on permanent files. The CDC permanent file system allows only seven characters for file names, so a shorthand system had to be devised and a manual log book kept. After models were no longer actively needed they were archived to the Central File System (CFS). The

CFS allows file names up to about thirty characters long, so that descriptive titles could be used. The approach used here was superior to the old UPDATE method because the engineer could use a screen editor instead of the cumbersome line-oriented directives required by UPDATE. However, one advantage of UPDATE was lost. When one model is derived from another, the UPDATE method provides an explicit indication (in the form of correction sets) of the differences between the two models. No such direct comparison is possible when separate files are kept for all models.

Comment cards were inserted in the various decks to describe the changes that were made.

4.4 How a Database might have Helped

If the database scheme proposed in Section 7 had been available when this study was done, it could have helped in three ways. It could have provided a better starting point for the effort, smoother procedures during the effort, and an end product that would be more accessible to future users.

If a well-documented and verified model had existed prior to this effort, a savings of at least 25% of the labor would have been possible, according to the engineer who did the work. The work would have been easier because it would not have been necessary to track models and file names manually. The database scheme proposed in Section 7 would have provided automated tracking of models, with tracing of the derivation of one model from another. It would have provided both the convenience of a screen editor and the traceability of UPDATE. It would have encouraged the engineer to provide adequate documentation at every step, while providing reversibility of all changes. Finally, although the CFS works well when it is up, it goes down frequently (or did when the study was done). This aggravation would have been avoided with a database implemented on a VAX. In summary, while the job got done, the engineer likened it to using a hand saw in comparison to a power saw.

The same engineer has stated that he would be able to find the files and notes and continue the study with relatively little difficulty if he were called on to do so. He also stated that it would be virtually impossible for anyone else to do so without his assistance.

5. B-1 and F-15E Case Studies: Well-documented Models

In this section, two large finite element aircraft analysis programs are reviewed. They were selected because they provide examples of well-documented models.

5.1 B-1 Model for an Airloads Research Study

Rockwell International developed a model of the B-1 aircraft number two (A/C-2) for NASA/Dryden Research Facility in the early 1980's (Ref. [4]). The purpose of the study was to utilize flight data acquired during B-1 flights and perform analyses of these data beyond the scope of Air Force requirements. Specifically, the structural model was to be used to calculate influence coefficients which would then be passed to the NASA aerodynamics code, FLEXSTAB. Although detailed models were available at Rockwell, it was decided to develop coarse models so that the aerodynamic studies could be executed efficiently. Seven substructures were modeled (wing, forward fuselage, aft fuselage, horizontal and vertical stabilizers, fairings, and nacelle) with a total of about 3520 grid points. The report appeared in five volumes (NASTRAN model plans; horizontal stabilizer, vertical stabilizer, and nacelle structures; wing structure; fuselage structure; and fairing structure).

This report is cited because it represents a thoroughly documented finite element model. The introduction begins by explaining the reason for the model, i.e., providing flexibility matrices of sufficient complexity for use with FLEXSTAB, an aeroelastic code. This is followed by brief physical descriptions of the aircraft as a whole, and each component.

There is an explanation of the DMAP code that was written to provide the required matrices for interfacing with FLEXSTAB. Following this is a package of engineering drawings that were used in developing the model.

Separate volumes are provided for each substructure. The wing volume, volume III, for example, begins with some engineering drawings and then gives an explanation of the NASTRAN input, consisting of several pages copied from the User's Manual. This would probably be unnecessary today with NASTRAN having become so well known. There is a page that explains the numbering scheme that was used (e.g., grid number XXYY lies on rib XX and spar YY). Similar conventions are given for element numbers.

Following this is an exhaustive series of plots generated by NASTRAN. It appears that every grid point and every element is labelled in at least one plot. For example, see Figures 3 through 6 which show all grid and element numbers for the outboard wing lug area.

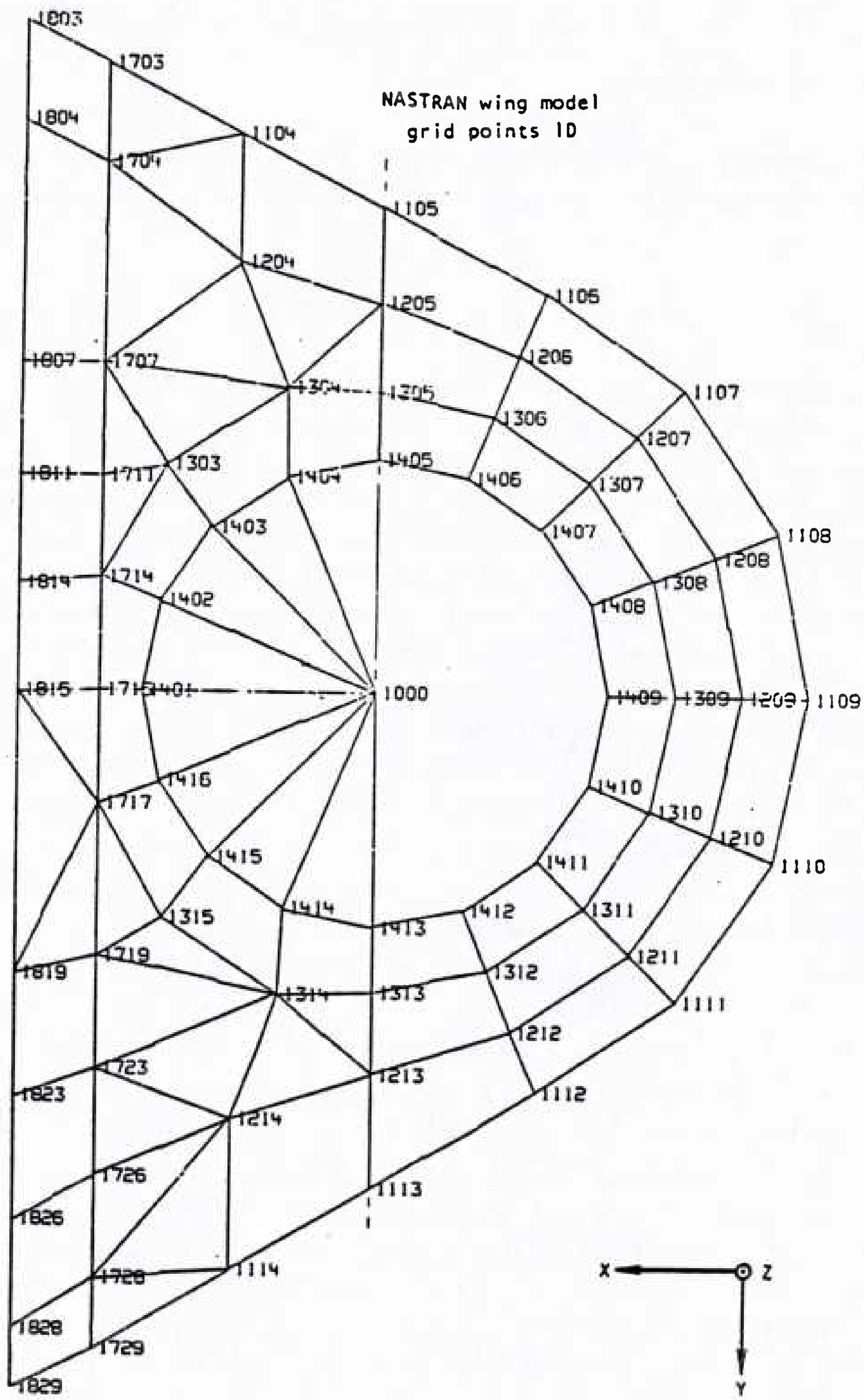

Figure 3. Upper outboard wing pivot lug grid points

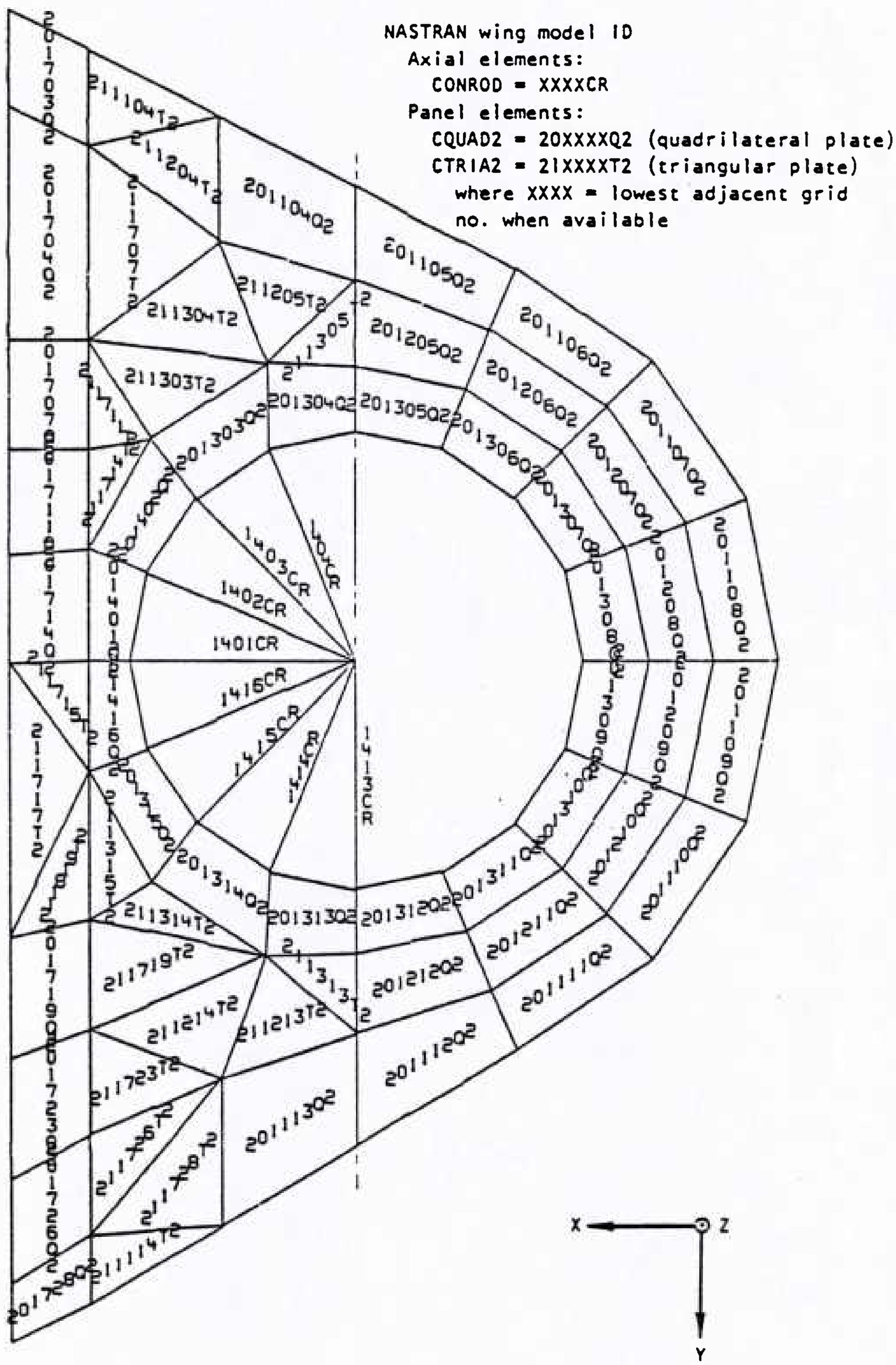

Figure 4. Upper outboard wing pivot lug elements

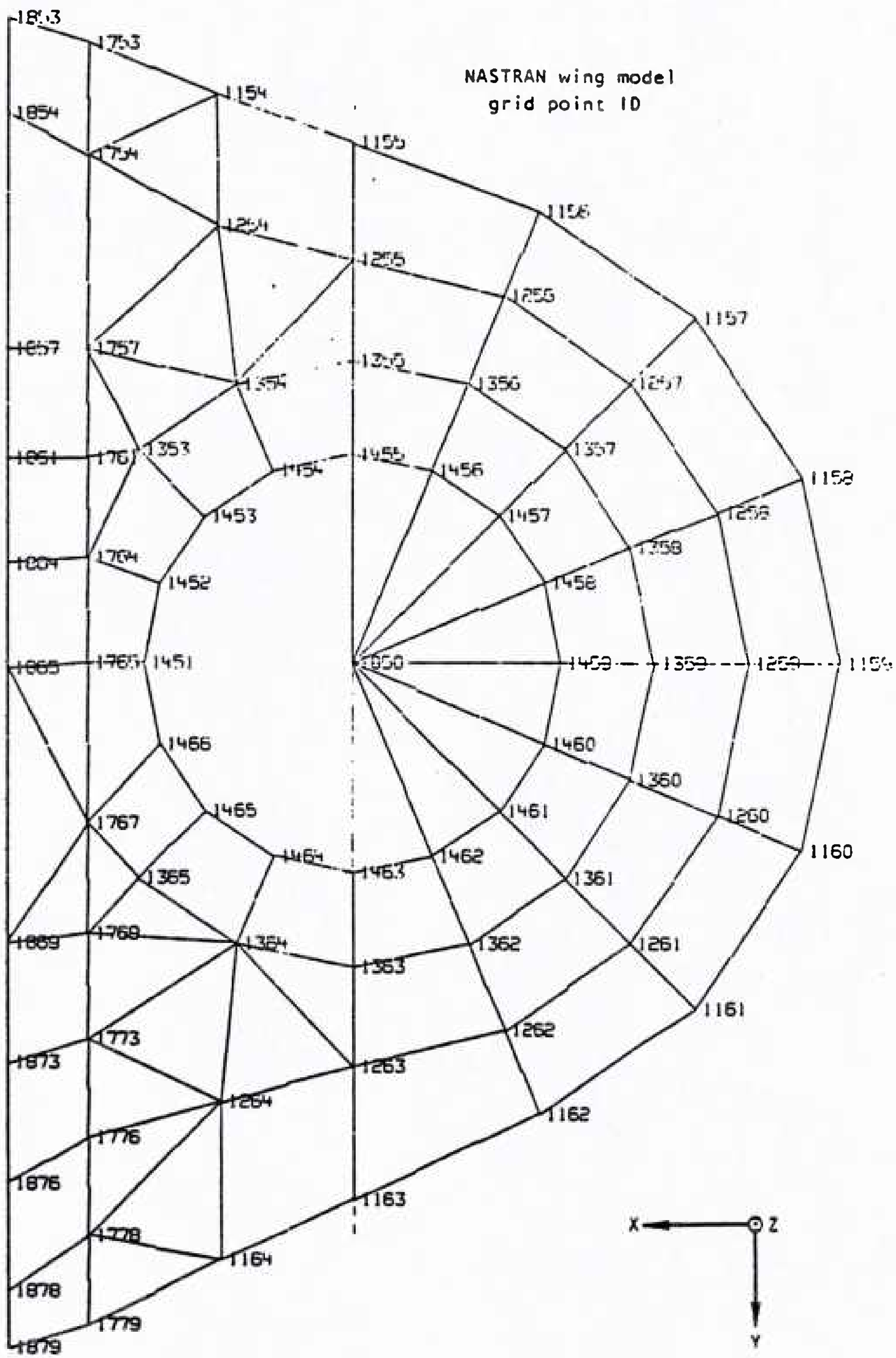

Figure 5. Lower outboard wing pivot lug grid points

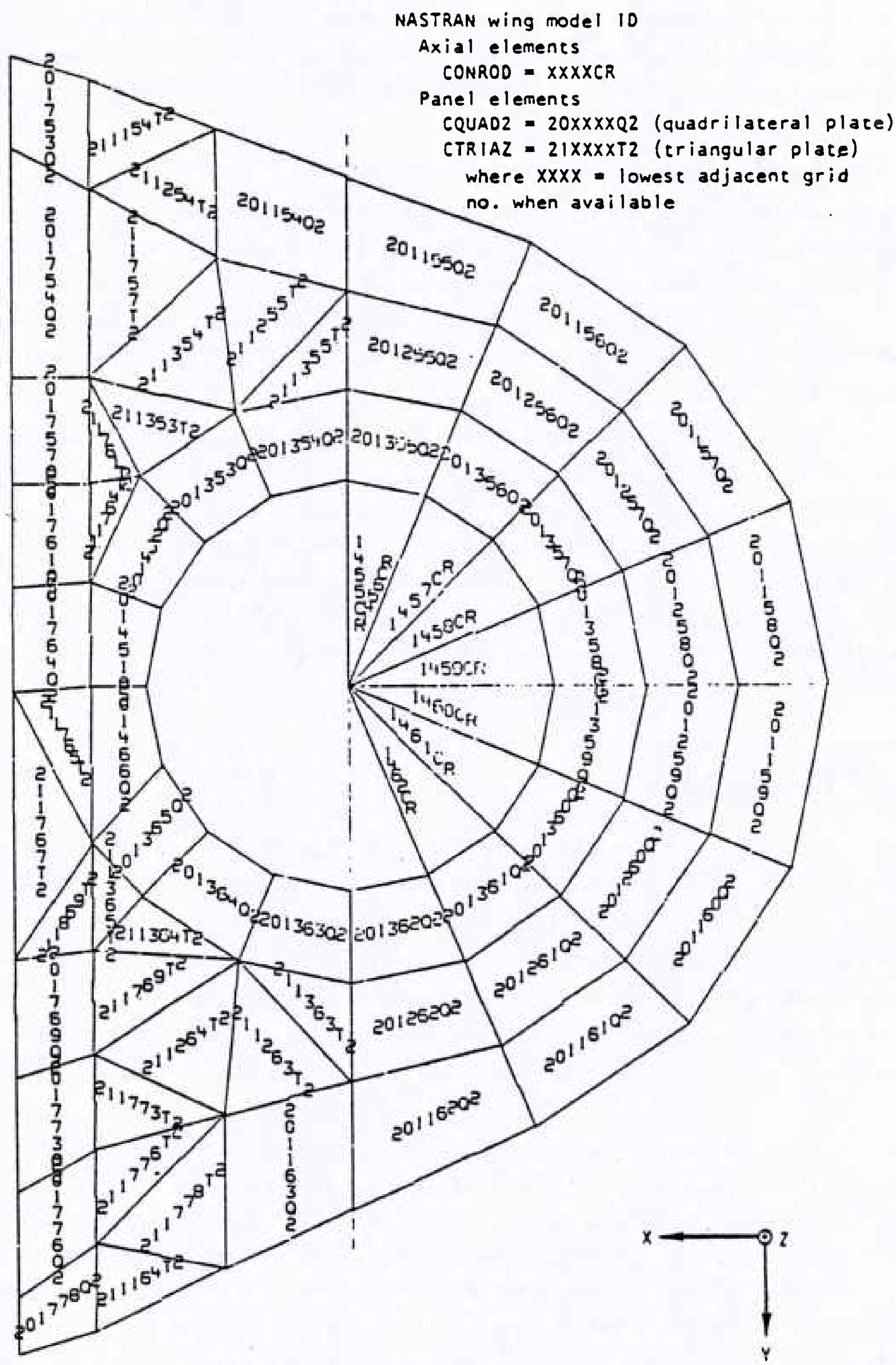

Figure 6. Lower outboard wing pivot lug elements

The text asserts that the model was checked for continuity, constraints, etc., using an interactive graphics code. Results are presented for unit loading at each of a number of selected influence coefficient points. Plots show selected displacements plotted versus results predicted by the detailed B-1 model. Good agreement is shown.

Finally, a sorted bulk data echo of over 4000 cards is given.

Thus, the report presents practically all the information that would be needed by an analyst assigned to pick up this model and use it. Engineering drawings are given, complete plots are presented, the numbering scheme is explained, and evidence of verification is given. The only category not covered is documentation of loads. There were no loads *per se*, since the purpose of the study was to develop influence coefficients.

As an aside, one wonders whether the project would be undertaken at all if it were proposed today. If the detailed model referenced in the report were available from Rockwell, and given today's tradeoff between engineering labor costs and computer costs, it might be better to simply run with the complex model. Second, one wonders whether any contractor other than Rockwell could have done the job. This would depend on whether the detailed model (which was of course created by Rockwell) could have been obtained by another contractor, and if so, whether it would have been documented adequately.

5.2 F-15E Model

Another contractor report is cited as an example of good documentation of loading conditions. This is the stress report for the F15-E aircraft, Ref. [5], specifically, section 11.9.2, Loading Conditions.

The section on loading conditions begins with a discussion of factors of safety, ultimate loads, thermal effects, and conservative combinations of engine thrust loads, flight loads, and cockpit pressures. Crash loads and pilot applied loads are also considered. The computer program used to develop load distributions is referenced.

Table 1 (copied from table 11.9.2-1 of the report) shows a listing of load conditions that were selected as critical for the forward fuselage. Each line of the table indicates the condition number used in NASTRAN, the engine thrust (max or min), Mach number, altitude, a brief description of the condition, limit load factors, cockpit pressure, a description in terms of the the effects on the structure, and an indication of the areas that are critical for the particular condition. This last item would be especially useful for someone picking up the model for the first time, intending to use it in an optimization study, for example.

COND NO.	F.E.M. COND NO.	ENG. THRUST	MACH NO.	ALT. FEET	DESCRIPTION	LIMIT LOAD FACTORS	ULT COCKPIT PRESSURE	TYPE LOADING	CRITICAL ITEMS OR AREAS
53	1-1			S.L.	Cockpit Burst Pressure		11.8 psi	Cockpit Pressure	Cockpit Frames, Floors, Tension Tie, Aft Cockpit Deck
54	1-2	Max	1.20	S.L.	Steady State Pull Up	$N_y = 0$ $N_z = 9.00$	0 psi	Down Bending & Shear	Upper & Lower Longerons, Vertical Shear Panels
55	1-3	Max	1.20	S.L.	Steady State Pull Up	$N_y = 0$ $N_z = 9.00$	8.85 psi	Down Bending & Shear with Cockpit Pressure	Cockpit Longerons, Frames, Skins, etc.
56	1-4	Min	1.20	S.L.	Steady State Pull Up	$N_y = 0$ $N_z = 9.00$	0 psi	Down Bending & Shear	Upper & Lower Longerons, Vertical Shear Panels
57	1-5	Min	1.20	S.L.	Steady State Pull Up	$N_y = 0$ $N_z = 9.00$	8.85 psi	Down Bending & Shear with Cockpit Pressure	Cockpit Longerons, Frames, Skins, etc.
58	1-6	Max	1.13	S.L.	Steady State Push Down	$N_y = 0$ $N_z = -3.00$	0 psi	Up Bending & Shear	Compression In Upper Longeron
59	1-7	Max	1.13	S.L.	Steady State Push Down	$N_y = 0$ $N_z = -3.00$	8.85 psi	Up Bending & Shear with Cockpit Pressure	Compression In Upper Longeron
60	1-8	Min	1.13	S.L.	Steady State Push Down	$N_y = 0$ $N_z = -3.00$	0 psi	Up Bending & Shear	Compression In Upper Longeron
61	1-9	Min	1.13	S.L.	Steady State Push Down	$N_y = 0$ $N_z = -3.00$	8.85 psi	Up Bending & Shear with Cockpit Pressure	Compression In Upper Longeron
62	1-10	Max	0.90	S.L.	L/H Rolling Pull Out	$N_y = .47$ $N_z = 7.24$	0 psi	Combined Bending, Shear & Torque	Side Longeron, Horizontal Shear Panels

Table 1. Forward fuselage design loading conditions

COND NO.	F.E.M. COND NO.	ENG. THRUST	MACH NO.	ALT. FEET	DESCRIPTION	LIMIT LOAD FACTORS	ULT COCKPIT PRESSURE	TYPE LOADING	CRITICAL ITEMS OR AREAS
63	1-11	Max	0.90	S.L.	L/H Rolling Pull Out	N_y = .47 N_z = 7.24	8.85 psi	Combined Bending, Shear & Torque with Cockpit Pressure	Side Longerons, Horizontal Shear Panels
64	1-12	Min	0.90	S.L.	L/H Rolling Pull Out	N_y = .47 N_z = 7.24	0 psi	Combined Bending, Shear & Torque	Side Longerons, Horizontal Shear Panels
65	1-13	Min	0.90	S.L.	L/H Rolling Pull Out	N_y = .47 N_z = 7.24	8.85 psi	Combined Bending, Shear & Torque with Cockpit Pressure	Side Longerons, Horizontal Shear Panels
66	1-14	Max	0.90	S.L.	R/H Rolling Pull Out	N_y = -.47 N_z = 7.24	0 psi	Combined Bending, Shear & Torque	Side Longerons, Horizontal Shear Panels
67	1-15	Max	0.90	S.L.	R/H Rolling Pull Out	N_y = -.47 N_z = 7.24	8.85 psi	Combined Bending, Shear & Torque with Cockpit Pressure	Side Longerons, Horizontal Shear Panels
68	1-16	Min	0.90	S.L.	R/H Rolling Pull Out	N_y = -.47 N_z = 7.24	0 psi	Combined Bending, Shear & Torque	Side Longerons, Horizontal Shear Panels
69	1-17	Min	0.90	S.L.	R/H Rolling Pull Out	N_y = -.47 N_z = 7.24	8.85 psi	Combined Bending, Shear & Torque with Cockpit Pressure	Side Longerons, Horizontal Shear Panels
70	1-18	–	–	–	Canopy Jettison	–	–	Maximum Canopy Remover Load	Canopy Jettison Mechanism
71	1-19	–	–	–	NLG Retract Actuation	–	–	NLG Retract Actuator	Actuator Support, F.S. 373.5 Floor Beam, Aft Cockpit Floor

Table 1. Forward fuselage design loading conditions (Continued)

COND NO.	F.E.M. COND NO.	ENG. THRUST	MACH NO.	ALT. FEET	DESCRIPTION	LIMIT LOAD FACTORS	ULT COCKPIT PRESSURE	TYPE LOADING	CRITICAL ITEMS OR AREAS
72	1-20	–	–	–	40 G Crash Fwd & Right	–	–	Inertia	Aft Cockpit Deck, Seat Rail Supports
73	1-21	–	–	–	20 G Crash Down		–	Inertia	Aft Cockpit Deck, Seat Rail Supports
74	1-22	–	–	–	1 – Cosine Dip (Dynamic Taxi Cond)		–	Nose Gear	Not Critical
75	1-23	–	–	–	Unsymmetric Braking L/H –Aft C.G.		–	Nose Gear	Not Critical
76	1-24	–	–	–	Unsymmetric Braking L/H –Fwd C.G.		–	Nose Gear	Keel Web, Trunnion Fitting
77	1-25	–	–	–	Unsymmetric Braking R/H –Aft C.G.		–	Nose Gear	Not Critical
78	1-26	–	–	–	Unsymmetric Braking R/H –Fwd C.G.		–	Nose Gear	Keel Web, Trunnion Fitting
79	1-27	–	–	–	0° Tow Aft @ NLG 0° Swivel		–	Nose Gear	Keel Web, Drag Brace Fitting
80	1-28	–	–	–	0° Tow Aft @ NLG 180° Swivel		–	Nose Gear	Keel Web, Drag Brace Fitting
81	–	–	–	–	Jacking @ NLG		–	Nose Gear	Trunnion Fitting

Table 1. Forward fuselage design loading conditions (Continued)

6. Standards for Delivery of Finite Element Models

The reasons why the Air Force should require its contractors to deliver finite element models developed in the course of their work have already been noted. In order to enforce this requirement on developers of future systems, a Mil-Standard must eventually be developed. This section presents some information on finite element models, pre-processors, and NASTRAN as a standard. This background information leads into a preliminary outline of a Mil-Standard directed toward delivery of finite element models.

6.1 Background on Finite Element Models and Their Use

We begin this section with a general discussion of finite element modeling as background for the subsequent discussion of delivery requirements for finite element models.

In finite element structural analysis, we are solving some kind of matrix equation which can be stated in a general way as

$$f\left(\mathbf{K}(\mathbf{U},\theta,\omega),\mathbf{M},\mathbf{B},\mathbf{U}(t),\dot{\mathbf{U}}(t),\ddot{\mathbf{U}}(t),t\right)=\mathbf{P}(\mathbf{K},\mathbf{M},\mathbf{U},t,\theta,\omega) \qquad (1)$$

Here we denote stiffness, mass, and damping matrices by $\mathbf{K}$, $\mathbf{M}$, and $\mathbf{B}$; displacements by $\mathbf{U}$, loads by $\mathbf{P}$, time by t, frequency by ω, and temperature by θ, showing that stiffness may be a function of displacement, temperature, or frequency, and that loads may be functions of stiffness, mass, displacement, time, frequency, or temperature. Thus, the familiar linear static analysis would be just

$$\mathbf{KU}=\mathbf{P} \qquad (2)$$

whereas a geometrically nonlinear transient analysis with follower forces would be written

$$\mathbf{K}(\mathbf{U})\mathbf{U}+\mathbf{B}\dot{\mathbf{U}}+\mathbf{M}\ddot{\mathbf{U}}=\mathbf{P}(t,\mathbf{U}) \qquad (3)$$

This example shows that nonlinearity is usually introduced implicitly (i.e., $\mathbf{K}$ and $\mathbf{P}$ are shown as functions of the independent variable $\mathbf{U}$). This leads to iterative solutions of the equations.

Based on this general formulation, we may state three basic questions facing the modeler:

1. What equations are to be solved; i.e., what is f? Do we have a static or dynamic problem, steady-state or transient, linear or nonlinear?

2. How to develop **K**, **M**, and **B**. This is determined by the layout of grids and elements, and by element types. These questions in turn are governed primarily by the objective of the analysis. Geometric symmetry may be used to advantage in laying out the model.
3. How to represent the load **P**. Is it static, transient, or steady-state? Does it vary with temperature, displacement, etc.?

Engineering expertise is needed to answer these questions, based on the nature of the structure, the excitations, and the physical phenomenon being modeled. Each of these questions is now discussed in turn.

6.1.1 Five Kinds of Finite Element Models

The kind of mesh that is chosen (coarse or fine) and the types of elements are determined primarily by the objective of the analysis. We may identify five kinds of NASTRAN finite element models which are distinguished mainly by the kind of elements that are used and the density of the mesh. The classifications are rather broad and overlap substantially, as will be seen. For aircraft structures, only three kinds are often used:

1. Static models
2. Dynamic models
3. Aeroelastic models

Two other kinds are less common in aircraft modeling:

4. Heat transfer models
5. Acoustic cavity models

Other finite element codes may support other analysis types, but not likely any that would be of interest in aircraft analysis.

Static models are designed to provide stress and deflection predictions. A high degree of mesh refinement is generally required for stress analysis for two basic reasons: (1) high stress gradients are commonly observed, and (2) when displacements are the independent variables, as is the case in all modern finite element codes, stresses are computed by differentiating the approximate displacements, thus introducing additional error which must be compensated for by increased refinement.

Dynamic models are generally used to compute natural frequencies and mode shapes. They may also be used to compute transient or steady-state displacements and accelerations. Such analyses require considerably less detail than static models

since mode shapes are usually distributed widely over the structure and are thus insensitive to local variations. Two exceptions may be noted: first, when gravity loads are included, there must be sufficient accuracy in the mass distribution to produce good loads. Second, dynamic stresses may also be of interest. In this case more detail must be introduced, at least locally. Also, if a dynamic analysis is desired but only a static model is available, it may be more economical to pay for the additional computer time required to carry out dynamic analysis with a static model than to expend the manual or semi-automated effort required to simplify the static model.

Aeroelastic models involve a mathematical model of the aerodynamics as well as a structural model. Aeroelastic models may be used to predict static aeroelastic stability using a real eigenvalue solution, and for dynamic aeroelastic stability.

Heat transfer models are generally similar to static models with regard to the kind of elements and their distribution. Heat transfer analysis capabilities are included in NASTRAN as a sort of byproduct of the structural analysis capability. The same elements are used, but NASTRAN generates heat capacitance and conductance matrices instead of stiffness and mass matrices. Temperatures take the place of displacements (thus only one degree of freedom per node), and heat sources and sinks take the place of loads. Prediction of accurate internal heat flux distributions is similar to prediction of accurate stresses in that generally fine meshes are required.

Acoustic cavity models appeared in NASTRAN as something of a spur capability which is not particularly relevant to aircraft analysis, but is mentioned here only for completeness. The method is intended for analysis of structure-acoustics interaction in rocket motors with axisymmetric geometry.

6.1.2 Symmetry

Most finite element models are general three-dimensional models. Others exhibit special symmetries which can be exploited by NASTRAN. Reflective symmetry is handled by simple constraints applied at points on symmetry planes. Cyclic symmetry is handled by special solution methods in NASTRAN. This category covers situations having rotational symmetry; that is, the structure looks the same after rotation about an axis through a given angle (which must divide 360 degrees evenly). Axisymmetry is a limiting case of cyclic symmetry. It is still supported in NASTRAN by special elements based on Fourier series expansions in the circumferential direction, but these special elements may be considered obsolete since the introduction of the more general cyclic symmetry capability.

It is not necessary that loads be symmetric in order to exploit geometric symmetry. In the case of reflective symmetry about the plane $x = 0$, for example, a general

load $\mathbf{P}$ may be decomposed into symmetric and anti-symmetric components; i.e.,

$$\mathbf{P}(x,y,z) = \mathbf{P}_S(x,y,z) + \mathbf{P}_A(x,y,z) \tag{4}$$

where

$$\begin{aligned} \mathbf{P}_S(x,y,z) &= \mathbf{P}_S(-x,y,z) \\ \mathbf{P}_A(x,y,z) &= -\mathbf{P}_A(-x,y,z) \end{aligned} \tag{5}$$

A static solution may be obtained by solving

$$\mathbf{K}_S\mathbf{U}_S = \mathbf{P}_S$$

and

$$\mathbf{K}_A\mathbf{U}_A = \mathbf{P}_A$$

and recovering the total solution

$$\mathbf{U} = \mathbf{U}_S + \mathbf{U}_A$$

for the $x \geq 0$ side, or

$$\mathbf{U} = \mathbf{U}_S - \mathbf{U}_A$$

for the $x \leq 0$ side. Even though two solutions are required, the cost is less than a solution of the full model because the matrix decomposition time will be less by a factor of about four.

Similar derivations are possible for solution of general loads acting on cyclic symmetric structures (Ref. [1]).

6.1.3 Equation Types

The simplest form of structural analysis is static analysis in which we solve the linear matrix equation shown in Eq. 2. Static analysis is justified when the loads change only slowly. In most cases, flight maneuver loads, for example, are treated as quasi-static.

In linear eigenvalue analysis we solve

$$(\mathbf{K} - \omega^2\mathbf{M})\mathbf{U} = \mathbf{0} \tag{6}$$

to obtain natural frequencies $f_i = \omega_i/(2\pi)$ and mode shapes $\mathbf{U}_i$. This kind of analysis is very important because frequencies and mode shapes tell a lot about the dynamics of a structure.

Static stability analysis is almost never required in aircraft analysis, but is mentioned here for completeness. The eigenvalue buckling problem

$$(\mathbf{K} + \lambda\mathbf{K}^d)\mathbf{U} = \mathbf{0} \tag{7}$$

is formed in terms of the "differential stiffness" $\mathbf{K}^d$, and solved for the lowest root λ. $\mathbf{K}^d$ is the linearized incremental stiffness associated with a particular applied load.

Dynamic loads may be classified as transient or steady-state. Transient problems are solved by forward integration of the equations of motion. Steady-state problems are important in the analysis of random excitations. Both problems are usually formulated in terms of modal superposition in which multipliers of a selected set of normal modes are used as independent degrees of freedom rather than node point displacements.

Most structural analysis is based on linearized equations of motion and linearized stress-strain laws. Nonlinearity is encountered more frequently in heat-transfer analysis, as when temperature-dependent thermal properties or nonlinear radiation laws are specified. In some cases, which are seldom encountered in aircraft analysis, one or both of these assumptions may not unjustified. In these cases special iterative analysis methods must be employed. Nonlinear analysis is usually difficult and time-consuming, requiring an analyst with special skills.

6.1.4 Definition of Loads

Definition of loads for aircraft analysis is basically a matter of defining the flight conditions to be used. Loads usually represent a certain load factor, altitude, airspeed, gross weight, store loads and many other considerations. Ground loads for taxi or landing landing impact may also have to be simulated. Obtaining these loads may require running other computer codes such as aerodynamic or taxi programs. Ideally a finite element model would come with a series of such loads representing the conditions which are critical for the design of the aircraft. Unfortunately, different loads are critical for different parts of the structure. A rolling pullout may drive the design of one component, while a different maneuver may be more important to another.

The manufacturer's stress report generally lists the criteria used in the design of each component and shows how the stress analysis was performed. These stress reports form a valuable adjunct to a finite element model, but they are usually published in limited quantities (only a few copies of each volume, while the volumes may run to a hundred or more) and are usually not available to most engineers. It is recommended that the Model Center have a copy of the stress reports available. Loads for a limited number of well-defined loading conditions should be part of the model.

6.2 NASTRAN as a Standard

NASTRAN was developed originally for NASA by contractors. Subsequently, commercial versions appeared, among which MSC/NASTRAN is predominant. While several other commercial finite element codes exist, none of them competes seriously in the aerospace industry. COSMIC NASTRAN, the original government version, still exists and is used at a few government installations, although we know of no aerospace companies that use it. Some aerospace companies continue to use in-house finite element codes, but nearly all use NASTRAN at least as an adjunct to their in-house code. FDL's ASTROS program also uses NASTRAN input format. These facts make it reasonable to specify NASTRAN format in the proposed Mil-Standard, and also to adopt NASTRAN format for storage of models in the Model Center.

The question remains: which NASTRAN format? The survey results in Section 3 suggest that most Air Force users would prefer MSC/NASTRAN format. This is probably true of aerospace companies as well. However, FDL has stated a preference for COSMIC NASTRAN, and for this reason, the Mil-Standard outlined in Section 6.6 requires contractors to translate their models into COSMIC NASTRAN format. The outline also calls for contractors to deliver their models in their original format. The first reason for this requirement is that some information may be lost in the process of translating from the original format to COSMIC NASTRAN format. The Model Center ought to have the original data as well as the translated data in order to understand what approximations were made in the translation process. Such approximations can be trivial or they may seriously effect the results predicted by the model. Second, many models will have been developed originally in MSC/NASTRAN format, and many (probably most) organizations that request models from the Center will want them in MSC/NASTRAN format. The Center ought to at least keep the MSC/NASTRAN versions along with the translated versions so that users who want MSC/NASTRAN format need not translate them back into that format. In Section 7 we show that the proposed database software is equally capable of storing COSMIC NASTRAN or MSC/NASTRAN data. In fact, it can store data for many other codes with somewhat reduced documentation capability.

6.3 Pre- and Post-Processors

Finite element pre-processors are programs (usually graphics-oriented) that can be used to generate finite element models in a semi-automated manner. Generally speaking, users define certain key nodes (at corners, for example) and then specify that a mesh of interior nodes and elements is to be filled in according to certain specifications.

Automatic mesh generation is convenient when applicable, but geometric irregularities in a structure may limit its usefulness. In these cases manual definition of many nodes and elements will still be necessary. In these cases, pre-processors are still valuable for the ability to view the model with interactive control of rotation, zoom, hidden surface removal, etc.

Pre-processors generally accept commands either from the keyboard or from command files. Since keyboard commands are not recorded permanently, command files are the best way to generate models in production work. In these cases the user may not pay much attention to the bulk data file that is generated by the pre-processor, considering the pre-processor command file to be the real source of the model and the focus of his effort. In other cases, however, manual editting of the bulk data may be necessary. If a user makes non-repeatable (or difficult-to-repeat) changes to a bulk data deck, he has then invalidated the pre-processor command file, making it difficult or impossible to go back to the pre-processor and make changes at that level. This also leads to the possibility that some unsuspecting future user may assume that the command file is still current. Thus we may distinguish three situations in the use of pre-processors:

1. Where little or no editting of the bulk data is required, the pre-processor command file should be considered the source of the model. Any editting of the bulk data should be done in a repeatable manner.[1]
2. Where extensive editting of the bulk data is required, it may be best to "burn bridges," abandoning the pre-processor once extensive changes to the bulk data have been made.
3. Borderline cases have to be handled with judgement, but it must always be clear whether the pre-processor command file is current or not.

NASTRAN has been selected as a standard finite element code for this effort (see 6.2). No such choice is possible for pre-processors, however, since no one code has reached the position of prominence that NASTRAN has reached among finite element codes. Therefore, no attempt will be made to develop standards that relate to pre-processing codes.

6.4 Validation of Models

It is very important to establish confidence in a finite element model, especially one obtained from another organization. Validation of models is by no means an exact science, but depends partly on experience and judgement. Nor is validation a simple yes/no judgement. Ideally, an estimate of the accuracy of the model is

[1]The use of HISTORIAN, discussed in Section 7, would be ideal for this purpose

desirable (e.g., within 5% or within 50%), or for dynamics, the range of frequencies over which it is valid.

As is mentioned in Section 8.3, there are some mathematical theorems regarding convergence of finite element models with increasing mesh refinement, but these are hardly ever useful in practice. For one thing, there is often not much choice about where to locate node points. Having defined node points at all the places dictated by the geometry of the structure (i.e., at stiffeners, cutouts, thickness changes, etc.), the analyst often finds his "budget" of node points exhausted, or nearly so.

There are a number of diagnostic checks performed by NASTRAN that should be checked as a first step in validating a model. Assuming a model is free of simple format errors and typographical errors, the next validation step would be generation of plots. These can be used to check visually for elements that are misshapen, node points out of place, etc. Also, the diagnostic program called RATS can be used to check models for bad or questionable geometry. Next, simple static loads can be applied. NASTRAN prints several diagnostic messages that can help uncover errors in element connections, poor constraint sets, etc. Simple node point singularities are detected automatically. More complex mechanisms or near-mechanisms can be detected by a matrix conditioning number (ratio of maximum factor diagonal to matrix diagonal). Acceptable values for this nondimensional ratio range from 10^5 to 10^7. A residual error ratio which is calculated for static analysis can also point to stiffness singularities. In dynamic analysis, spurious strain energy in rigid body modes can indicate improper constraint sets. All these diagonistics should be checked where applicable.

Loads often provide a good standard with which to validate models. A set of known loads that provide a set of known or measured displacements for the actual structure provide a benchmark that can be used to check the model for continuity, connectivity, and constraints. Correlation of such data provides confidence that the model is an accurate representation of the real structure. Confidence in the model is a very important factor in finite element analysis, since there can be errors that are not easy to detect. Another method of providing loads to run a check on a model is the use of structural influence coefficients using point loads as was done during the creation of the the B-1A model. This is useful if there is sufficient data to check against. If vibration data is available, from a ground vibration test for example, a normal modes analysis of the model can help verify the stiffness of the model if the mass is known to match.

In dynamic problems, mode shapes should be checked thoroughly by generating plots. Improper stiffness and masses will often show up as unrealistic mode shapes. Also, the diagnostic messages that are provided with the various eigenvalue solution methods should be checked to insure that no roots have been skipped.

Validating a model can require a great deal of effort. As the survey results

reported in Section 3 indicate, Air Force agencies receiving models from contractors often have no practical choice but to assume that the contractor has created a good model. It can be argued that manufacturers have the best data and knowledge of the structure and so the models the create ought to be good. Of course, a major goal of the present effort is to make it unnecessary to accept models on faith, by requiring evidence of validation along with delivery of models.

6.5 Supporting Documentation

The value of a finite element model depends heavily on the availability of supporting documentation, especially when a model is delivered from one organization to another. Documentation may include reports, plots, sketches, and comments in the bulk data deck.

6.6 Mil-Standard for Delivery of Finite Element Models

The need for a standard to require developers of Air Force aircraft to deliver the finite element models that they generate has already been discussed in Section 2. In this section we discuss the proposal for a standard in more detail. The outline below is based largely on Venkayya's proposal (Ref. [2]), but with some additional ideas and a somewhat different arrangement.

6.6.1 Background on Mil-Standards

Typically a standard imposes requirements and performance standards and recommends techniques for compliance. Structural requirements for aircraft are contained in two basic documents, Mil-A-87221 and Mil-Std-1530A. A Mil-Standard for the acquisition of finite element models should ideally be a separate document, although it could conceivably be made part of Mil-A-87221, during its next review and update cycle. The requirements of such a Mil-Standard have been addressed by the Air Force. A sample Data Item Description was drafted in 1985 (Ref. [2]) and addresses in detail the type of data that must be supplied.

Through the MIL-PRIME program, the Air Force has been working to streamline the acquisition process by improving the quality of specifications and standards applied to individual contracts. The goal is a to eliminate overspecification by tailoring documents to specific weapons systems. Each MIL-PRIME document consists of a specification or standard tailored to the specific situation. An associated handbook contains rationale, guidance, and lessons learned for each requirement and its associated verification. By the end of 1987, fifty-four MIL-PRIME development documents were available for program use (Ref. [6]). In the past, delivery of finite element models has generally not been a requirement, even though the contractor

may have been paid for the work involved. If such delivery is to made a requirement, a stringent Mil-Standard must be developed to ensure that models contain all the documentation needed to insure their usefulness. The requirements of this Mil-Standard should be such that it would not require or even accept tailoring to an individual program. The temptation to water down the model requirements must be avoided.

The creation of a Mil-Specification or standard is an involved process. It is certainly beyond the scope of Phase I to try to create such a document. However, since the authors have given some consideration to the need for such a document, a rough outline of such a Mil-Standard based on the format of Mil-Std 1530 is suggested.

6.6.2 Outline of the Proposed Mil-Standard

This outline is based on Venkayya's DID (Ref. [2]) with some added material and a somewhat different order of topics.

1. Scope

    1.1 Purpose. The purpose of this standard is to describe the Air Force Model Program, define the overall requirements, and specify methods of contractor compliance. This standard shall be used by:

        1.1.1 Contractors in developing an airframe for a particular weapon or system

        1.1.2 Government personnel

    1.2 Applicability. This standard is directly applicable to:

        1.2.1 Future airplane systems

        1.2.2 Airplane systems procured by the Air Force, but developed under another agency such as the USN or the FAA.

        1.2.3 Airplanes undergoing a major modification.

2. Referenced Documents

    2.1 COSMIC NASTRAN manuals

    2.2 ANSI specs for ASCII tape format

    2.3 (others as required)

3. Definitions

    3.1 Finite Element Model

- 3.2 Analysis types
  - 3.2.1 Static Analysis
  - 3.2.2 Dynamic Analysis
    - 3.2.2.1 Undamped normal modes
    - 3.2.2.2 Damped normal modes
    - 3.2.2.3 Transient analysis
    - 3.2.2.4 Steady-state frequency response analysis
    - 3.2.2.5 Random analysis
  - 3.2.3 Heat Transfer Analysis
    - 3.2.3.1 Linear steady-state analysis
    - 3.2.3.2 Non-linear steady-state analysis
    - 3.2.3.3 Linear transient analysis
    - 3.2.3.4 Non-linear steady-state analysis
  - 3.2.4 Aeroelastic Analysis
  - 3.2.5 Combined Structure-Control system Analysis
- 3.3 Meta-models

4. Model Delivery Requirements

   - 4.1 The contractor shall deliver to the Air Force all finite element models that were used in verifying structural integrity.
   - 4.2 Contractors shall not be required to use any particular finite element code in their analysis work. Models shall be delivered in the format used by their particular code. If some code other than COSMIC NASTRAN is used, a translated version of each model shall also be provided. The translated version will conform to the input requirements of COSMIC NASTRAN. In cases where COSMIC NASTRAN does not provide a capability supported by the contractor's in-house code, the closest capability in COSMIC NASTRAN will be substituted where possible.
   - 4.3 Contractors shall deliver to the Air Force any meta-models that were used in generating the finite element models that are delivered. The contractor shall identify the pre-processing code for which the meta-model was developed. Meta-models shall be in the form of ASCII input files, as used by the contractor. There will be no translation requirement.
   - 4.4 All models must be delivered on standard half-inch computer tape, in ASCII format. The contractor may use a different format subject to approval by the project officer. Tapes must be accompanied by a written list of the contents of each file on the tape.

5. Documentation Requirements

   5.1 General. For each model that is delivered, a complete set of documentation will be required.

   5.2 Identification of the aircraft. For each model that is delivered, the following shall be documented:

      5.2.1 Name and configuration version.

      5.2.2 Identification of documents and drawings from which the model was generated. Copies of these documents and drawings shall be provided if they are not otherwise available to the Government.

      5.2.3 A key diagram showing the location of the component being modeled in relation to the rest of the structure.

   5.3 Documentation applicable to all model types

      5.3.1 A brief discussion of the physical phenomenon being modeled.

      5.3.2 A discussion of the fineness or coarseness of the model.

      5.3.3 Any symmetry conditions that were used to advantage, including the type of symmetry (reflective or rotational) and its location.

      5.3.4 Documentation of element types. A list of element types used and the rationale for each shall be provided.

      5.3.5 "Smearing" approximations. A common practice in finite element modeling is to represent areas with complex geometry (such as surfaces with small holes) by equivalent uniform sections. Where such practices have been employed, they shall be explained here.

      5.3.6 Material properties. All materials properties shall be explained and referred to applicable Mil-Standards, with reasons given for any deviations from those standards.

      5.3.7 Documentation of constraint sets. For each set of constraints (boundary conditions), an explanation of the reason for the constraints. If constraint sets are to be combined (by NASTRAN SPCADD cards), this must be documented.

      5.3.8 Validation. The contractor shall explain how the model was validated. This discussion encompasses diagnostic messages from the finite element code, comparison to known or expected results, and reference to test data if such is available.

   5.4 Documentation of static models.

      5.4.1 Load sets. For each set of loads, an explanation of each shall be provided, including a categorization (static, gravity, thermal, centrifugal, or other special situations).

5.4.2 If load sets are to be combined by NASTRAN (using LOAD bulk data cards), these combined sets must be documented.

5.4.3 Where nonlinear analysis is employed, information specific to the nonlinear aspects must be presented.

5.4.3.1 The nature of the nonlinearity (finite displacements, nonlinear elasticity, plasticity) and the reason why nonlinear behavior was expected.

5.4.3.2 Control parameters that were used in the iterative solution, and evidence of convergence

5.5 Documentation of dynamic models.

5.5.1 The frequency range over which the model is valid.

5.5.2 The reduction process that was used (if any). This may include subspace iteration, generalized dynamic reduction, or Guyan reduction. In the latter case, an explanation of the analysis-set degrees of freedom shall be provided.

5.5.3 Any nonstructural masses that were used.

5.5.4 For dynamic response analysis, the following must be provided. These requirements apply to both transient analysis and steady-state frequency response and random analysis.

5.5.4.1 The source of the loading, and the way in which its frequency distribution or time history were derived.

5.5.4.2 The kinds of damping that were used (viscous or structural) and how values were arrived at.

5.5.4.3 Dynamic solution parameters. For either transient or steady-state analyses, where modal superposition is used, the frequency at which modes were truncated shall be justified.

5.5.4.3.1 For transient analyses, an explanation of the time step value that was chosen.

5.5.4.3.2 For steady-state frequency response analysis, an explanation of the frequency increment.

5.5.5 Aeroelastic analyses. When aeroelastic analyses are performed, the structures model shall be described as required under sections 5.3 and 5.4. This section pertains to documentation of the aerodynamic modeling.

5.5.5.1 The aerodynamic theory being employed shall be described (piston theory, etc.)

5.5.5.2 The lifting surfaces for which aerodynamics are being modeled shall be enumerated and described physically.

5.5.5.3 The aerodynamic parameters shall be enumerated (altitude, mach number, etc.)

5.5.5.4 The kinds of force and displacement transformations between the structural grid and the aerodynamic grid shall be explained.

5.5.5.5 Provisions for rigid body modes, if any, in flutter analyses.

5.5.5.6 Where aeroservoelastic analysis is employed or anticipated, data must be presented in a state space formulation.

5.6 Documentation of heat transfer models

5.6.1 Derivation of material properties with references to Mil-Standards.

5.6.2 Heat sources and sinks

5.6.3 Boundary conditions

5.6.4 Analysis type (transient or steady-state; linear or nonlinear)

5.6.5 Transfer of temperatures to static stress analyses, if applicable.

5.7 Special analysis types. This section shall cover any special analysis types not enumerated above, including interdisciplinary analyses such as structure-control system or fluid-structure analyses. A full explanation of the coupling method shall be provided.

6.6.3 Comments on the Outline

No attempt has been made to formulate proper legal phrases for a Mil-Standard. This is a matter for specialists.

This outline is based on Venkayya's DID (Ref. [2]). In one section, he spells out the ingredients of a static model (nodes, elements, material properties, etc.). We have not included this because it gives the appearance of a specification about how to create models. The intent here is to specify only delivery requirements and not guidelines for creating models. We assume that the models have already been validated and thus they must include all the necessary ingredients.

Acoustic cavity analysis was not mentioned specifically in Article 5 since it is seldom applicable to aircraft analysis. Such analyses would be incorporated under in Article 5.7.

Meta-models were mentioned in Article 4.3, and are discussed in Section 8. No standards can reasonably be imposed regarding meta-models. However, delivery of this data is considered valuable even if it is for a code which the Air Force does not have. It could be useful merely for gaining additional understanding of the model that it generates.

6.6.4 Costs

It must be understood that these requirements will impose costs upon contractors which will ultimately be reflected in their bids. Superficially, it might seem that the only costs involved would be writing a tape, bundling up some documents, and shipping them, and these would be nominal. In fact, the real costs would result from contractors' perceptions (real or imagined) that they were being subject to increased exposure and liability. They would thus expend extra effort in verifying and documenting any models that were to be delivered.

It is very difficult to quantify such costs. However, it is reasonable to assume that they would be a fraction of what would be charged under a contract that called for generation and development of a model of the same system.

Another relevant point is the benefits that would accrue to both the contractor and the Air Force as a result of these requirements, aside from the delivery *per se*. The authors know from long experience that having to explain a model to a colleague is one of the most effective ways of debugging it. This is so even when the colleague merely sits and listens. Another fact of life is that developers, having invested so much energy in a model, tend to assume it is complete before there have been sufficient checks. It is quite likely that in documenting and verifying a model in preparation for delivery, contractors would discover shortcomings that had previously not come to light. Such discoveries could prevent potentially catastrophic problems with the models. In any event, the additional efforts would increase the contractor's confidence in his own model.

Another way to approach the costs issue is to assume for a moment that delivery requirements had been in effect all along and that someone was proposing eliminating them in order to save money. They would have to argue that contractors would bid lower because they could take less care in their modeling and could skip some of the documentation and verification efforts. Such arguments would not likely be taken seriously. This would be especially true if the proposed Model Center had been in existence for some time, and if models delivered by contractors had been used to advantage by the Air Force.

7. A Proposed Database for Finite Element Models

The basic function of the envisioned Center is to collect, process, store, and distribute finite element models and information about those models. The Center will not be successful unless this information can survive after the personnel who generate it have left. Typically, developers of finite element models (also developers of computer software) do not realize the extent to which they rely on memory, nor how quickly they can forget. This usually becomes clear only when work is interrupted (by a vacation, for example). A good way to address this problem is by thoughtful design of information-handling systems. The software, procedures, rules, etc., that constitute such systems should do the following:

1. Anticipate the kinds of descriptive information that is most useful;
2. Encourage users to enter such descriptions when new models or modifications are entered;
3. Structure the data in a manner that reflects the way engineers generate and use it.

This does *not* imply that expensive or elaborate systems will be needed. It *does* mean that the system design should be guided by engineers who are experienced users of finite element software, and should be implemented by personnel who know how best to implement these ideas using existing software wherever possible.

The rest of this section discusses the problems involved in maintaining and documenting finite element models, reviews past approaches to the problem, and recommends a software solution that will be simple, effective, and efficient.

7.1 Past Approaches to Model Maintenance

The problems faced by engineers who must update and maintain finite element models are very similar to those faced by software developers who must maintain source code. Both cases involve maintenance of large ASCII files which are subject to continuing modification and the associated problems of tracking, verification, etc. Also, small changes can produce subtle and unexpected changes in the results produced by the software or the model. As computer hardware developed over the years, so did the methods available for source code maintenance, and the same methods have been adapted to some extent for finite element models.

At first, punched cards were used exclusively. While physical possession of a card deck provided a certain sense of confidence, there were many problems. Card decks were difficult to identify and were vulnerable to physical deterioration. If one

wanted to create a modified version of a model and still save the original, one could always get the cards duplicated and modify the copy. But then the changes would probably not be documented, and subsequent changes to the original might not be applied to the copy.

Later, magnetic tapes became available to store card-image files such as source code or finite element models. Manufacturers provided utilities that enabled users to make corrections to a basic file on tape without destroying the original. SLP on the UNIVAC 1107 was one such system; IBM supplied another for its 7094. However, during the late 1960's, Control Data mainframes (6400, 6600) became predominant in scientific computing. Most finite element analysis was carried out on these machines, and most users took advantage of CDC's UPDATE utility for model maintenance. This approach still relied on punch cards as the primary input medium, but provided users with a means for tracking modifications and for retaining multiple modifications of a single basic file.

The basic sequence of operations with UPDATE was as follows:

First, a user partitioned his source file into sections called "decks." Each deck was given a name which was punched on a *DECK card. Deck names, if chosen wisely, helped somewhat in documenting the model.

Next, the source file was submitted to UPDATE which read the deck and created a "program library" file which was stored on tape (or later, on permanent disk files). File names for these program libraries provided another tag that could help document models. UPDATE also produced a printed listing showing a unique identifier for every line in the file. This listing had to be retained by the user. Wise users also kept their original card decks because frequent system problems in those days made data storage on magnetic media unreliable.

Then, in order to make corrections, a user prepared a "correction deck" which was identified by a correction set name (another opportunity for identification). Each such deck consisted of *INSERT and *DELETE directives which referred to cards in the original deck by their sequence numbers. By submitting both the "old program library" and the correction deck, UPDATE could produce a modified source file that could be submitted to a compiler or a finite element code. The obvious advantage was that these changes were reversible. Furthermore, one could maintain several independent correction decks (corresponding to various damage cases, for example) that could each reference the original model.

It often happened that corrections became so numerous that the correction decks began to rival the original deck in size. In these cases one could direct UPDATE to write a "new program library" (NEWPL) which included the indicated corrections. Deleted cards were not really removed from these libraries, but instead were marked "inactive." Thus even after saving a NEWPL, one could reverse the effect of correction sets by means of *YANK and *YANKDECK directives. An irreversible step

was also possible in which one created a resequenced "source" file.

The process of creating update correction sets was still somewhat tedious, however. Users had to prepare UPDATE directives as well as revised data cards, and then keypunch them (or submit filled-in forms to the keypunch department). In the late 1970's, video terminals became available; screen-oriented editors soon followed. These utilities made it much easier to make corrections because one could see the corrected file as it was changed on the screen, and it was not necessary to retype whole lines if only a few characters were to be changed. Users embraced these screen-oriented systems enthusiastically, but there were still problems. With only a screen editor to make changes, users lost the discipline provided by UPDATE: there was no tracing and no reversibility except to the extent that users saved backup copies of old versions of files.

The introduction of preprocessors such as PATRAN, GIFTS, GRASP, etc., has increased productivity in finite element modeling, but these packages in themselves have not solved the logistical problems of finite element modeling. If anything, in adding a new step to the modeling process, they have introduced new pitfalls. That is, it is possible to generate a model with a preprocessor and then modify it manually. After making manual changes, one might want to return to the preprocessor to make changes at that level, at which point the manual changes would be lost.

With the proliferation of computer power both in the PC world and in minicomputers, a number of source code maintenance tools have become available. Many of these have advanced features such as macro expansion, "include" files, and screen editors oriented toward a particular high-level language. Most of these features are not relevant to finite element models. One could of course envision a bulk data-oriented screen editor, but such a development is beyond the scope of this effort, and besides, would tend to counter the trend toward model generation by automated pre-processors.

The solution that is presented in the following paragraphs was motivated by a desire to have both the advantages of UPDATE and the advantages of a screen editor. Another goal was to handle all user interaction through a friendly, screen-oriented interface.

7.2 The HISTORIAN/DATATRIEVE Approach

Among the engineers who contributed to this effort, three (Dr. Gibson, Mr. Negaard, and Mr. James) are experienced users of NASTRAN. Over the years, they have gained experience with and understanding of the engineering and mathematical aspects of finite element modeling. More important for our purposes here, they know from first-hand experience the logistical problems that this proposal addresses. All three have had to work with models developed by others, and have experienced the

intense frustration that can arise when these models are poorly documented. They also understand the kinds of revisions or variations that engineers typically apply to models, such as error corrections, new load cases, different materials, damage cases, etc.

Mr. Tenorio has been applying database technology to engineering data management problems for many years. While he knows the computer science aspects of database technology thoroughly, he also understands the user's point of view. In particular, he knows that users generally have developed certain approaches to their problems, and that these approaches should be respected even though they may not be optimal from a computer science point of view.

The database approach recommended here was developed jointly by Mr. Tenorio, Dr. Gibson, and Mr. James. While Dr. Gibson and Mr. James explained what users would like to do, Mr. Tenorio developed ideas about how best to implement the suggested functions. The solution outlined here is believed to be powerful but simple; it does not introduce sophistication for the sake of sophistication. It encourages users to provide ample documentation but does not straightjacket them with excessive requirements. The hope here is that new users would soon see the usefulness and friendliness of the software, and would not perceive it as a burden.

7.2.1 The Three Proposed Software Components

The proposed software consists of three components:

1. HISTORIAN: a text management system based on CDC's UPDATE product.
2. DATATRIEVE: a general-purpose non-relational database product provided by Digital Equipment (available on the FDL VAX).[2]
3. A driver to interface between the user on the one hand, and HISTORIAN and DATATRIEVE on the other hand. This driver will be developed as part of Phase II and is tentatively called FEMREC.

Some background on these products is in order here.

HISTORIAN is a commercial text management system similar to CDC's UPDATE utility, which was described in the previous section. Most engineers who ever used CDC or Cray computers are familiar with UPDATE. The two main advantages of HISTORIAN over UPDATE are (1) it runs on all major computer types, and more importantly, and (2) it relieves users of the burden of manual preparation of correction sets. This second feature is accomplished by means of

[2]SMARTSTAR is an alternate database product that provides essentially the same functionality as DATATRIEVE, while offering some minor advantages. DATATRIEVE will be assumed in this section with the understanding that SMARTSTAR or some other product may be substituted in Phase II.

a utility called HISTGEN. HISTGEN allows users to extract a source file from a HISTORIAN library (version n), modify this file using a screen editor (producing version $n+1$), and then automatically generate the *DELETE and *INSERT cards (i.e., the correction set) that could be applied to version n to produce version $n+1$. The user then has the advantages that UPDATE offers in terms of named, reversible correction sets, and at the same time, he retains the flexibility and convenience of a screen editor.

Notwithstanding these advantages, HISTORIAN by itself is inadequate for the problem at hand. In particular, we need some of the features of a true database. In particular, users need to move up and down the hierarchy of the database, issuing inquiry commands with or without qualifiers at any time. They need to extract, replace, or add data as needed. DATATRIEVE provides these features, but would be inadequate by itself because it is not oriented toward storing large volumes of text data. Hence the recommended approach takes advantage of both systems. Driver code (FEMREC) interfaces between users, HISTORIAN, and DATATRIEVE. This code will provide a convenient and friendly screen-oriented user interface with on-line help, selection of functions from menus, and prompts for information that may be needed when new data is entered. The provision of a driver makes it unnecessary for engineering users of the system to know anything about HISTORIAN or DATATRIEVE. In fact, they need not even know that these codes are being used. This is not only true for users who extract models from the database, but also for those who update the database. Only the developers of FEMREC (primarily Mr. Tenorio of ATA) will need to understand these products. Having written a very similar code recently, Mr. Tenorio will be able to write the new code at low cost and with low risk. However, the software will be easy for others to modify later because it will be based on HISTORIAN and DATATRIEVE, which are well documented and widely used.

It should be noted that the proposed software will be specific to VAX computers. This is not expected to be a problem because there should only be one copy of the database, maintained on a particular computer at FDL, and FDL already has VAXes available which could be used in Phase II. There should not be any need to port the code to a different type computer. However, before any commitments are made in Phase II, this issue will be re-examined, and the possibility of using a database product other than DATATRIEVE that runs on more than one machine type will be investigated.

Another point to emphasize is that the only purpose of this software is to store and retrieve models and information about those models. No manipulation of the bulk data is contemplated. For example, we would not attempt to check the bulk data for format errors, duplications, etc. Nor would we attempt to operate on the data in any manner, such as merging models, redefining node points in terms of different coordinate systems, or translating models between COSMIC and MSC

format. Where such software aides seem appropriate, they will be left to separate codes, which are discussed in Section 10.

A further point of interest is that with the exception of descriptor records which are discussed in Sections 7.2.3 and 7.3.4, there is nothing about this database that requires the use of NASTRAN. That is, GIFTS steering files, PATRAN driver files, or input to many other codes could also be stored.

7.2.2 Engineering Considerations Underlying the Proposed Database

The design of the proposed database, which is detailed in the following section, is based on some observations about the kinds of models that will be involved, the kinds of modifications that are likely, and how users will want to interrogate the database and extract data. Some discussion of these assumptions is in order here.

To begin with, we are dealing with finite element models of aircraft. Seldom if ever is an entire aircraft analyzed in a one-shot run (i.e., without benefit of substructuring). Thus it is appropriate to take as our primary unit of information a model of a single component such as a wing, landing gear, horizontal stabilizer, etc. (However, this arrangement does not preclude the possibility of storing a complete model as a unit.) Of course, interface nodes and elements will appear in two or more component models. As currently envisioned, there will be no attempt to reconcile interface nodes and elements when two or more components are joined together. Other software may be developed for this purpose in Phase II.

While our primary unit of information is a component, means must be provided to accommodate the kinds of changes that users might desire. Four kinds of changes are contemplated.

First, users may want to make one-time modifications that they will not want to save in the database. After extracting bulk data, the user could make such changes easily, using a familiar text editor. If after running NASTRAN, however, he decides that these changes ought to be permanent, this can be done at that time using one of the other three methods.

Second, users may simply want to make permanent corrections to correct errors or obvious shortcomings. The user will be expected to validate such changes, unless they are quite trivial, by re-running NASTRAN. Although the changes would be expected to be permanent, the provisions of HISTORIAN will make it possible to undo these changes should the need arise. When entering such modifications in the database, the user will be asked for a short explanation of the change. The user's name along with the current date and time will be entered in the database. HISTORIAN will automatically be invoked to generate and save a correction set.

Third, users may want to generate a new version of a component which is substantially different from the current one. Such changes could arise in two ways:

First, there could be a new version of the component which is physically different from the current one. An example would be a wing whose wing box is made out of composites instead of metal. Second, a new model might be generated or acquired whose purpose is different from the original. Thus, a simplified version of an existing stress model might be needed for dynamic analysis purposes, and would be much coarser than the stress model. Since these models both reference the same piece of the aircraft, they should logically carry the same component name, and should be distinguished by a version identifier.

Fourth, users may which to generate variations on a basic model. The differences between these modified models and the basic model would be minor in terms of the amount of data that is actually changed. The most obvious example is damage assessment, where the model is repeatedly modified by removing or changing a few elements to simulate the damage. A second example would be local refinement of the model in a certain area in order to improve stress predictions. Dozens of such variations could be generated, and it does not make sense to generate an entire new component record, with its accompanying full bulk data deck, for each such variation. The approach proposed here is to store only HISTORIAN correction sets for these variations, not a whole new dataset. This gives rise to another database file in which information about variations is stored, along with pointers to another HISTORIAN library in which the actual correction sets are stored.

To summarize, we have defined four kinds of changes, with specific terms to describe each:

1. One-time changes which are not saved in the database.
2. Error *corrections* which are expected to be permanent.
3. New *versions* of a component which, while they still represent the same part of an aircraft, are substantially different either physically or in modeling approach. Different versions of the same component are identified by the same component name but different version names.
4. *Variations* which represent small changes to a basic component that represent model refinements, tradeoff studies, damage tolerance, etc.

It should be re-emphasized that in none of these cases does the user become involved with HISTORIAN details such as *DELETE and *INSERT directives. All user interaction goes through FEMREC which handles all such matters. Also, the distinctions among corrections, new versions and variations are somewhat arbitrary, as they are based on the extensiveness of and the reasons for the changes that are involved. The choice would be entirely up to the user. The primary payoff is that future users will be alerted to the nature of the differences (extensive or not). A minor payoff results when variations are used in terms of reduced storage requirements.

As the next section shows, the database files will include various descriptors that will aid in documenting models and changes to models. However, it is very desirable from an engineering point of view to be able to document the contents of a bulk data file in more detail. Users often do this by means of comment cards in the bulk data deck itself. However, database storage of these comments would be more useful because they could be identified, retrieved, and displayed so much more easily than by searching with a text editor or scanning listings. For this reason, an additional database file type is proposed in which user comments are stored and are referenced back to individual bulk data cards, to user-defined card sets, or to sets that are recognized by NASTRAN (loads and constraints). In cases where existing bulk data decks already have comments in them, it may be advisable to write simple software that would retrieve these comments and present them to the database software for inclusion in the database.

7.2.3 Four Kinds of Database Files

Our database file will thus have one primary file per component (**component files**). It should be emphasized that these records will not store the actual bulk data, only information about the component and pointers that will enable FEMREC to direct HISTORIAN to extract the actual bulk data.

A second file type, **correction files**, will contain correction sets that are applied to the basic model. These files are intended to store correction sets that constitute error corrections, in contrast with the variation file which holds changes made for engineering reasons. It is expected that the corrections stored in correction files would be permanent, but they would be stored here to provide traceability and the possibility to retract corrections should the need arise.

Third, **variation files** will contain correction sets that constitute variations on a basic component model.

Finally, **descriptor files** will be used to document bulk data cards, as discussed above. For example, a particular MAT1 card may be described as "Aluminum, T6065." A PSHELL card may be described as "Upper skin thickness, stations 49.125 to 63.5." A set of GRID cards might be identified as "GRIDs lying on spar at station 101.25." A set of elements might be identified as "bulkhead C-3." Finally, an important class of cards that need to be identified are those having set numbers selectable through the case control deck. The two primary classes of this type are load sets and constraint sets (of which there are two kinds: SPC and MPC). Thus the first kind of documentation records would be those that refer to a single card, and these would easily be identified by their card type and ID (e.g., "MAT1" and "101"). Second would be sets of cards which would be identified by sets of ID's such as elements 401, 403, 410-420, and 429. Third would be load sets or constraint sets which would simply be identified by the words "loadset" or "SPCset" or "MPCset"

and an ID number. It should be possible to provide software that would check for additions, deletions, or changes to members of these sets and to solicit comments on the changes for inclusion in the database.

An important function of FEMREC is its screen-oriented interface with the user. For example, users could see a list of available components. Having picked a component, they might be presented with lists of versions or variations. They could also look through the comments that document a particular component. They could select data for retrieval, make changes, or add new components or versions, etc.

Some scenarios that illustrate these concepts are presented in Section 7.4.

7.3 Layout of the Proposed Database

This section presents the layout of the database as presently envisioned. Four files are defined: component files, correction files, variation files, and descriptor files. For each file, descriptions and examples are given for each data item.

While this arrangement has been rather carefully thought out, it would of course be subject to revision during Phase II in response to suggestions by FDL engineers or other interested parties. Furthermore, it would not be difficult to add more data elements that might seem advisable as experience is gained in Phase II.

The descriptions below are in the following format:

DATA ELEMENT

DESCRIPTION

EXAMPLE(S)

7.3.1 COMPONENT Files

This database file serves two primary purposes: to describe a model and to point to the model data itself. There is also pointer data and status information. There is one record in this file for every model that is tracked. The following records are defined:

SYSTEM

Name of the major system being modeled

F16

COMPONENT-NAME

Name of the physical component being modeled

STBD-WING

VERSION-NAME

Name defining a particular version of this component

Composite wing box

COMPONENT-DESCRIPTION

Brief description of the model including the coarseness/fineness of the grid selected, the elements selected and the boundary conditions.

Fine model of the F-16 starboard wing (composite wingbox) for stress analysis

COMPONENT-AUTHOR

Name and affiliation of the original model author(s)

McDonnell-Douglas Corp., St. Louis, MO
J. A. Smith, R. L. Jones, F. W. Johnson

SOFTWARE

Defines the finite element code to be used

COSMIC NASTRAN, MSC/NASTRAN, GIFTS, PATRAN

DEVELOP-DATE

Date when the model was entered into the database

30Jun88

ANALYSIS-CATEGORY

Type of analysis performed by this model

static, dynamic, aeroelastic, heat transfer

HISTORIAN-NODE

Name of the DecNet node that contains the required library

FDLVAX

HISTORIAN-DIRECTORY

Name of the disk and directory that contains the library

DISK$USER:[FEMODELS]

HISTORIAN-FILE

Name of the data file that contains the HISTORIAN library

F16.HIS

HISTORIAN-DECK

Name of the deck in the HISTORIAN library that contains the input data file

WING

RESULTS-COMMENTS

Description of the results of running this model

Static case 1 produces 5.26" wing tip displ.

REFERENCES

Description of additional reference material

General Dynamics report 82.1028A

CORR-FLAG

Indicates if modifications have been made to the basic model

Y/N

VERSION-FLAG

Indicates if there are versions of the component model in the database

Y/N

VARIATION-FLAG

Indicates if there are variations of the model in the database

Y/N

7.3.2 CORRECTION Files

This database file contains the data elements needed to briefly describe corrections that have been made to a basic model. Note that corrections are sequential, and they are *backward* in the sense that they would take an existing file back to its previous status.

SYSTEM

Name of the major system being modeled to which this correction set applies.

F16

COMPONENT-NAME

Name of the model to which this correction set applies

Wing

CORR-NAME

Name given to the this correction

ELEM-FIX

CORR-DESCRIPTION

Brief description of why these corrections are being made as well as some indication of the ramifications of applying or not applying these changes

QUAD4 elements around outboard edge of flap were found to have interior angles approaching 180 degr.

CORR-AUTHOR

Full name of the Author

G. R. Negaard

CORR-DEVELOP DATE

Date when these modifications were made

30Jun88

CORR-HISTORIAN-FILE

Name of the data file that contains the HISTORIAN library

F16MODS.HIS

CORR-HISTORIAN-DECK

Name of the deck in the HISTORIAN library that contains the correction set to be applied to the basic model

MODS1

7.3.3 VARIATION Files

These database files contain data elements needed to briefly describe variations made to the basic model. As explained in the previous section, a variation involves minor changes to the basic model and is hence described in terms of a correction set which references the original model data.

SYSTEM

Name of the major system being modeled to which this variation applies

F16

COMPONENT-NAME

Name of the model on which this variation is based

STBD-WING

VERSION-NAME

Name given of the version of this component model

Composite wing box

VARIATION-NAME

Name given to the new VARIATION of the basic model

STIFFER-STRINGER

VARIATION-DESCRIPTION

Brief description of the changes made to the basic model

Tried stiffening stringer on center line

VARIATION-AUTHOR

Full name of the Author

Lt John Jones, AFWAL/FIBR

VARIATION-DEVELOP-DATE

Date when this variation of the model was developed

30Jun88

VARIATION-HISTORIAN-FILE

Name of the data file that contains the HISTORIAN library

F16VARIATIONS.HIS

VARIATION-HISTORIAN-DECK

Name of the deck in the HISTORIAN library that contains the correction set to be applied to the basic model

Wing-comp

VARIATION-RESULTS

Description of the results of running this model

Wing tip displacement reduced to 4.42"

VARIATION-REFERENCES

Description of additional reference material

CSA report 89.1026

7.3.4 DESCRIPTOR Files

This database file contains data elements used to document individual cards or card sets within a bulk data deck.

SYSTEM

Name of the major system being modeled to which these descriptors applies

F16

COMPONENT-NAME

Name of the model to which these descriptors apply

Wing

VERSION NAME

Name of the version to which these descriptors apply

Wing-22

CARD-IDENTIFIER

Name of the card or card set to which these comments apply

MAT1, PSHELL, GRID, LOADSET, SPCSET, MPCSET

ID

ID number(s) of the cards being described

101,403,410-420

COMMENTS

Description associated with the set of cards identified by the CARD IDENTIFIER and ID

Grids for spar at station 121.23

7.4 Scenarios for Use of the Database

We now attempt to flush out the descriptions given above by depicting scenarios for use of the proposed database. The intent is to show how things work from the user's point of view.

Upon entering FEMREC, the user would see a top-level menu displayed on the screen. Several of the major menu items are described briefly in the following text:

7.4.1 Browsing Through the Database

Users must be able to find out what is in the database. One might simply call for a list of all models currently stored, for example. Alternatively, one could qualify the search by asking for a list of all wing models, all models created since 1985, all models that use composite materials, etc. Having picked a particular component, further browsing functions would be made available by a second-level menu. One could ask for a list of all the variations of a particular component, for example, one could display all descriptors records (see 7.3.4) that refer to material cards.

7.4.2 Adding a New Component Model

An engineer who has received a new model will presumably spend some time studying it and making NASTRAN runs. At some point, he will be ready to enter the model into the database. The Center should establish standards that models would have to meet before they qualify for entry in the database, and users should get approval from the director of the Center before entering a new model. Alternatively, unproven models could be entered for test purposes if they were clearly marked as such.

The engineer would pick the top-level function called "enter new model." He would then be prompted for information about the model, as indicated in Section 7.3.1 above. He would then be asked if he wanted to enter information about

individual cards or card sets in the bulk data. Such information would not be mandatory, but just asking for it at this point would encourage users to provide this kind of valuable information. Thus, referring to listings and plots, the user could enter information about grid point and element locations, thicknesses, material properties, load sets, and constraint sets. In each case, up to about 200 characters of descriptive text could be entered, and this text could be referred to a single card, to cards sets recognized by NASTRAN (load and constraint sets), and to arbitrary card sets (such as lists of elements).

7.4.3 Adding or Revising Descriptive Material

It is unlikely that a user could or would want to enter all descriptive material at a single sitting. Thus, another top-level menu item would enable revision or addition of descriptive material for a model. This would be particularly useful in the case of bulk data descriptions, which could run to hundreds of lines of text. Note that revision or addition of descriptive material would not constitute modification of a model, as tagged by "CORR-FLAG" in 7.3.1. Only changes to the bulk data itself constitute a modification.

7.4.4 Variations and Corrections

In the preceding discussion, we distinguished between a "variation" and a "correction." Although the user would be free to classify a particular change as either a variation or a correction, the intent is that corrections would fix clear errors or shortcomings, and would be expected to be permanent (subject to revocation, however; see 7.2.2). Variations would be intended for changes such as

1. Strengthening a particular area of a structure;
2. Introducing more refinement into a region subject to stress concentrations;
3. Changing element types (e.g., QUAD4 instead of SHEAR elements; BAR instead of ROD);
4. Removal or alteration of some elements as part of a damage tolerance study.

Some of these changes might appear to be candidates for permanent modifications. For example, if refinement of a model did indeed provide better stress predictions, one might be tempted to discard the old model and retain only the refined model. This would probably not be wise because future users of the database could benefit from seeing how this refinement improved the results.

Some bulk data cards are grouped in sets by NASTRAN (loads and constraints). Thus new load sets or constraint sets could be added without disturbing the old ones, so that these cases might best be handled as corrections rather than variations.

7.4.5 Extraction of Bulk Data

Having picked a particular component model and perhaps a particular version and/or variation thereof, the user may want to extract the bulk data. Another menu item would be provided for this purpose. The bulk data file could then be edited by the user before being submitted to NASTRAN. If the results were satisfactory, the user might wish to enter the edited file in the database either as a new component (if the changes were extensive), as a correction (if the changes constituted error corrections), or as a variation (if the changes were limited in scope, and were not intended to replace the basic model). In the case of variations or corrections, HISTORIAN would automatically generate the correction set, and FEMREC would store it in the database.

7.4.6 Deletions

Finally, there would be a function to delete a variation or a correction. Also, if a variation proved to be quite extensive, a user might decide it ought to be classified as a new component rather than a variation. This could be accomplished simply by extracting the bulk data, deleting the variation, and submitting the bulk data as a new component model.

7.5 Operations Automatically Carried Out by FEMREC

This section briefly describes the operations that would be carried out by FEMREC in response to the various kinds of user actions. Users would not have to anything about these matters; they are included here only to show how the proposed system would work.

The basic organization is shown in Figure 7. Note that all user interaction takes place through FEMREC, which displays information one screen at a time, with user input prompted by menu displays. There is no direct user interaction with DATATRIEVE or HISTORIAN.

Figure 8 shows the actions that take place when a new component model is added. In response to user commands, FEMREC generates a command file which causes HISTORIAN to read a small directive file along with the user bulk data and then add the bulk data to its bulk data library file. Figure 9 shows what happens when the user requests extraction of a bulk data file for a particular component model. In this case the HISTORIAN directive file causes it to access its bulk data library file and write the requested bulk data on a file. Figure 10 shows the same operation except with a variation requested. In this case HISTORIAN first accesses the library in which it stores one correction set corresponding to each variation. The proper set is extracted and submitted to HISTORIAN which now references

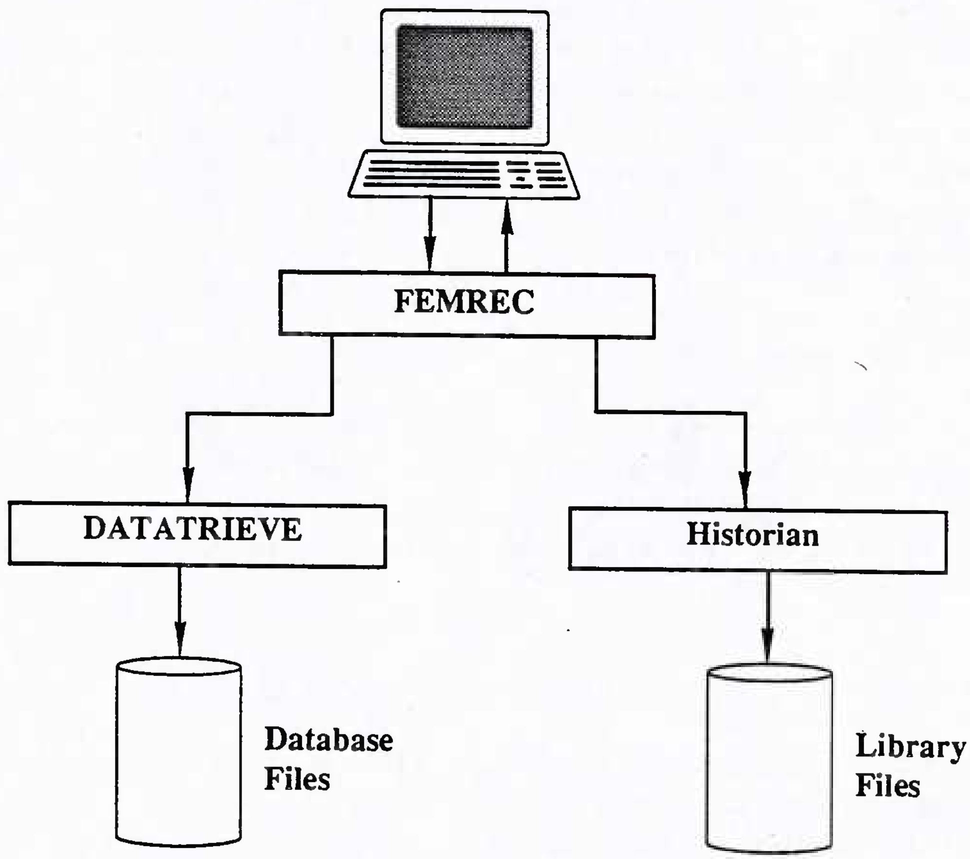

Figure 7. Basic database organization

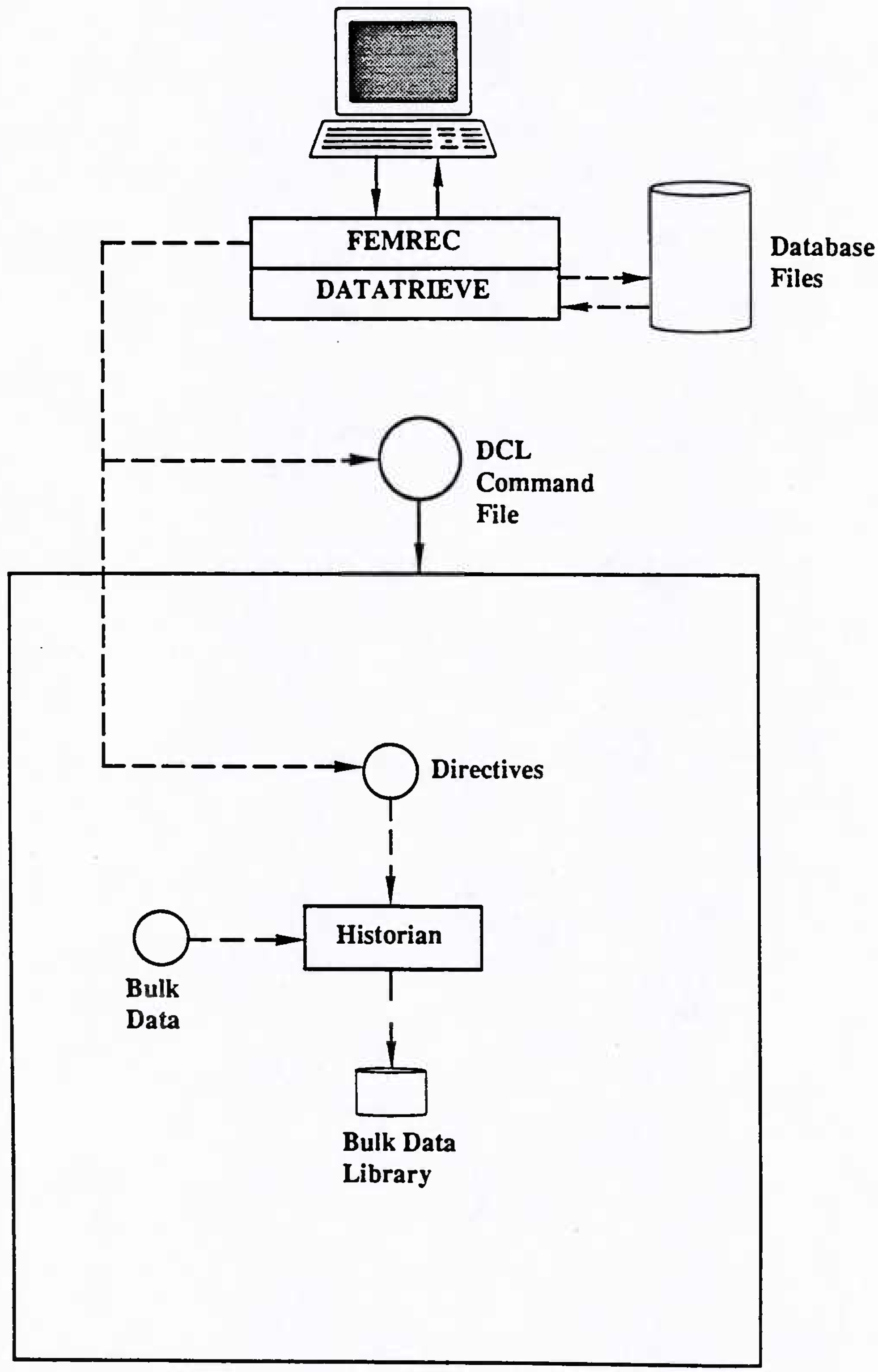

Figure 8. Adding a new component model

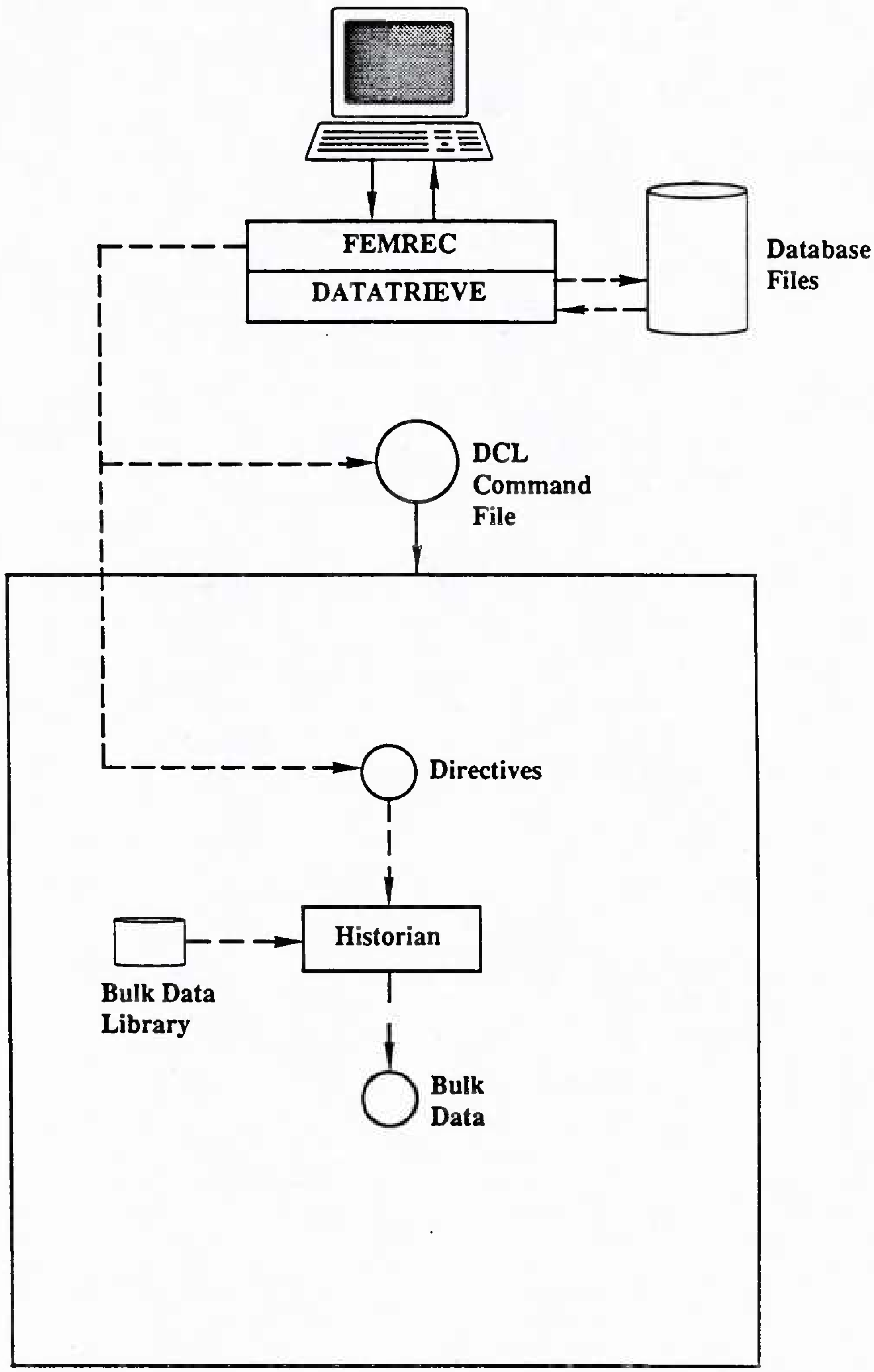

Figure 9. Extracting bulk data

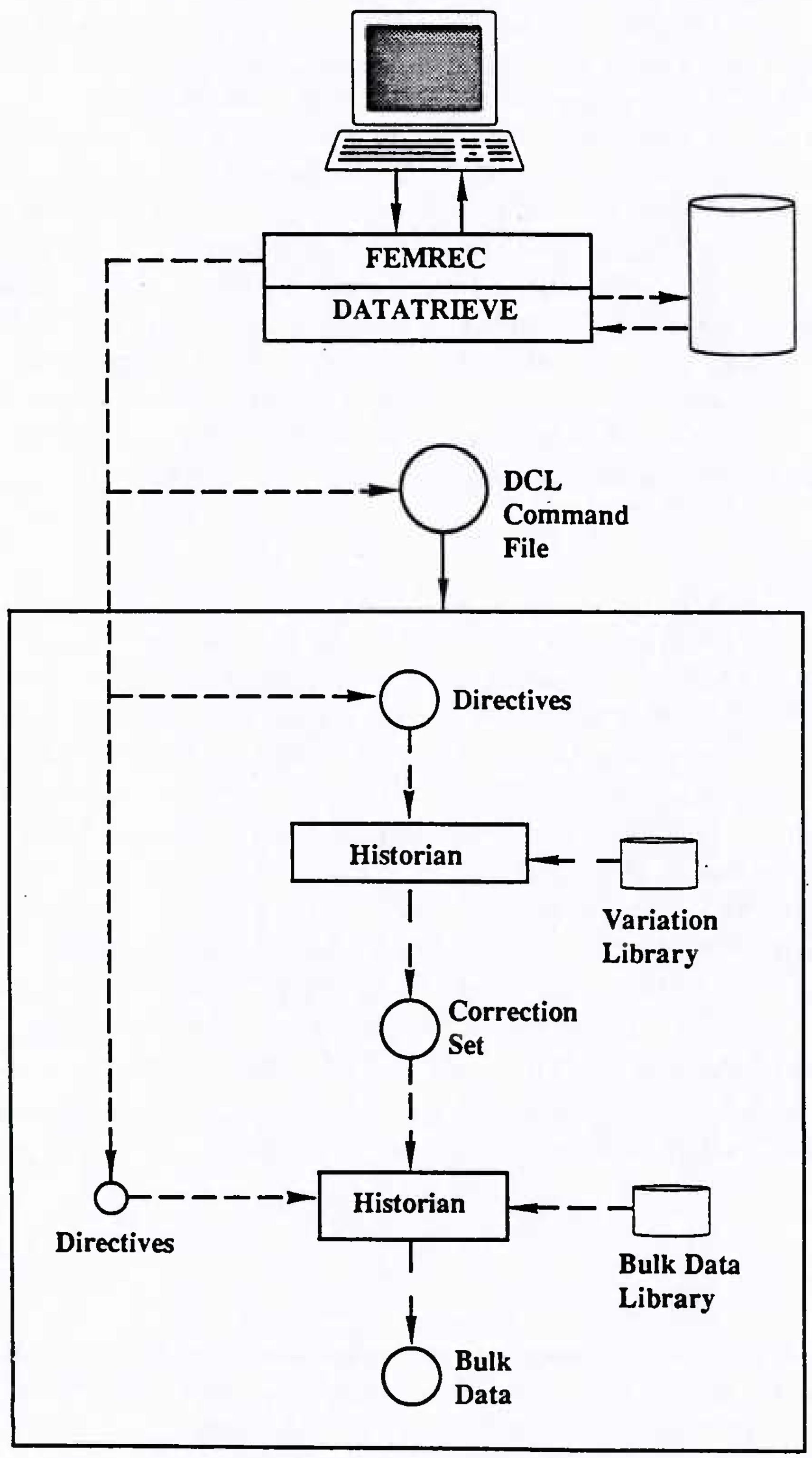

Figure 10. Extracting bulk data with a variation

its bulk data library, extracts and modifies the proper data, and writes it to a file for the user. Figure 11 shows a user creating a new variation of a component model. Previously, he had extracted the bulk data he wanted and then had modified it with a text editor. HISTORIAN is asked to compare the modified bulk data with the old bulk data, generate a correction set that could be used generate the new data from the old, and then store the correction set in its variation library. Finally, Figure 12 shows the process that is used to add a new correction to a component model. As with variations, HISTORIAN is called to generate a correction set. This correction set is then combined with each variation correction set (if any exist) to see whether any conflicts exist. Assuming no conflicts exist, HISTORIAN is called once more, this time to generate a *backward* correction set, i.e., one that generates the old file from the new. This correction set is then stored in the "corrections" database. The reason for this approach is that we want to store the revised bulk data, not the original. Recall that corrections are expected to be "semi-permanent."

7.6 Security

As discussed in Section 2, security will be an important concern. The models collected by the Center will be very valuable to the Air Force and must be safeguarded appropriately. On the other hand, the Center will only be useful if information about models becomes widely known in the Air Force, and perhaps in contractor organizations as well. The HISTORIAN/DATATRIEVE approach provides a natural solution to these seemingly contradictory requirements. This is because descriptive information is kept in one set of files (DATATRIEVE database files), while the actual bulk data is kept in HISTORIAN library files. Thus the HISTORIAN library files could be kept secure while the database files would be freely available. The HISTORIAN files could be kept on tape cartridges which could be kept under lock. The database pointers that locate HISTORIAN files in terms of directory name and file name could be modified to refer to a tape cartridge.

A tempest version of the MicroVAX computer has recently been announced. When the Center is ready to begin full operations, acquisition of such a system will be considered.

7.7 Summary

This section has described the logistical problems encountered in documenting and maintaining finite element models, and has proposed a rather specific solution in terms of available software. It is our belief that this solution will provide an effective tool for use in the proposed Center. All the software should be ready for use within a few weeks after Phase II begins. This will leave time to gain experience with live model data and to refine the system in the process. Also, it would be easy to add

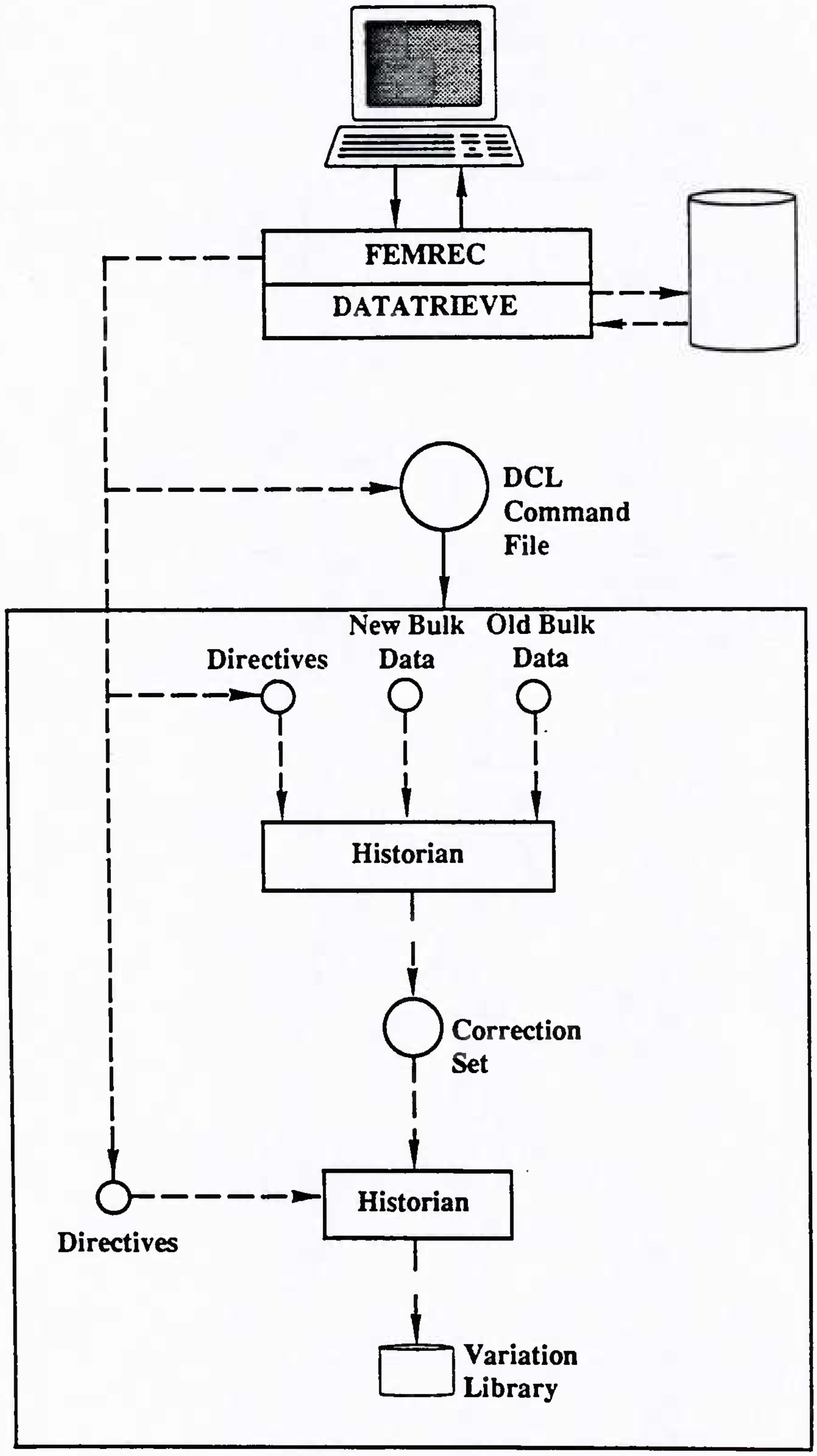

Figure 11. Creating a new variation

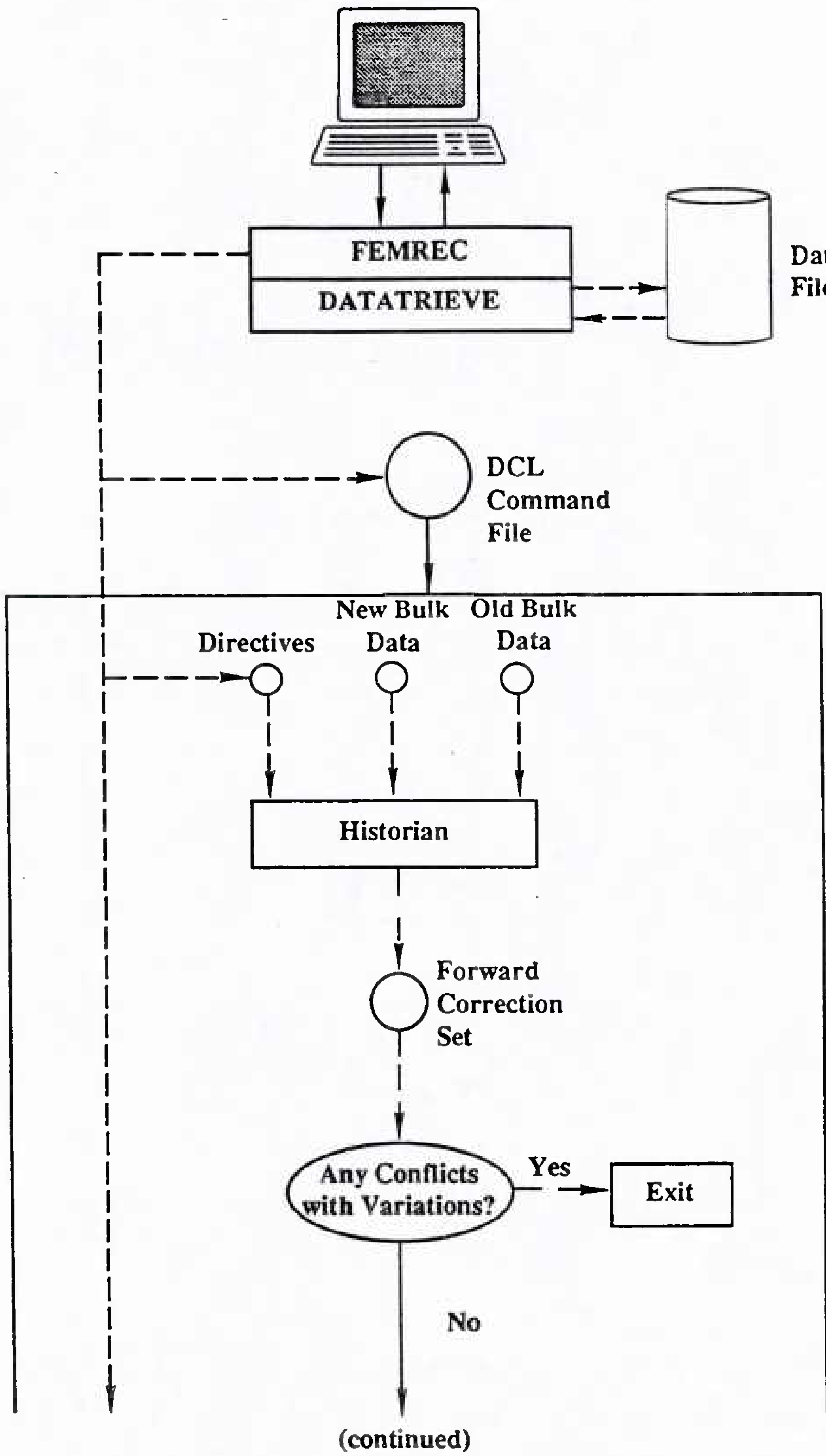

Figure 12. Making a correction

(continued)

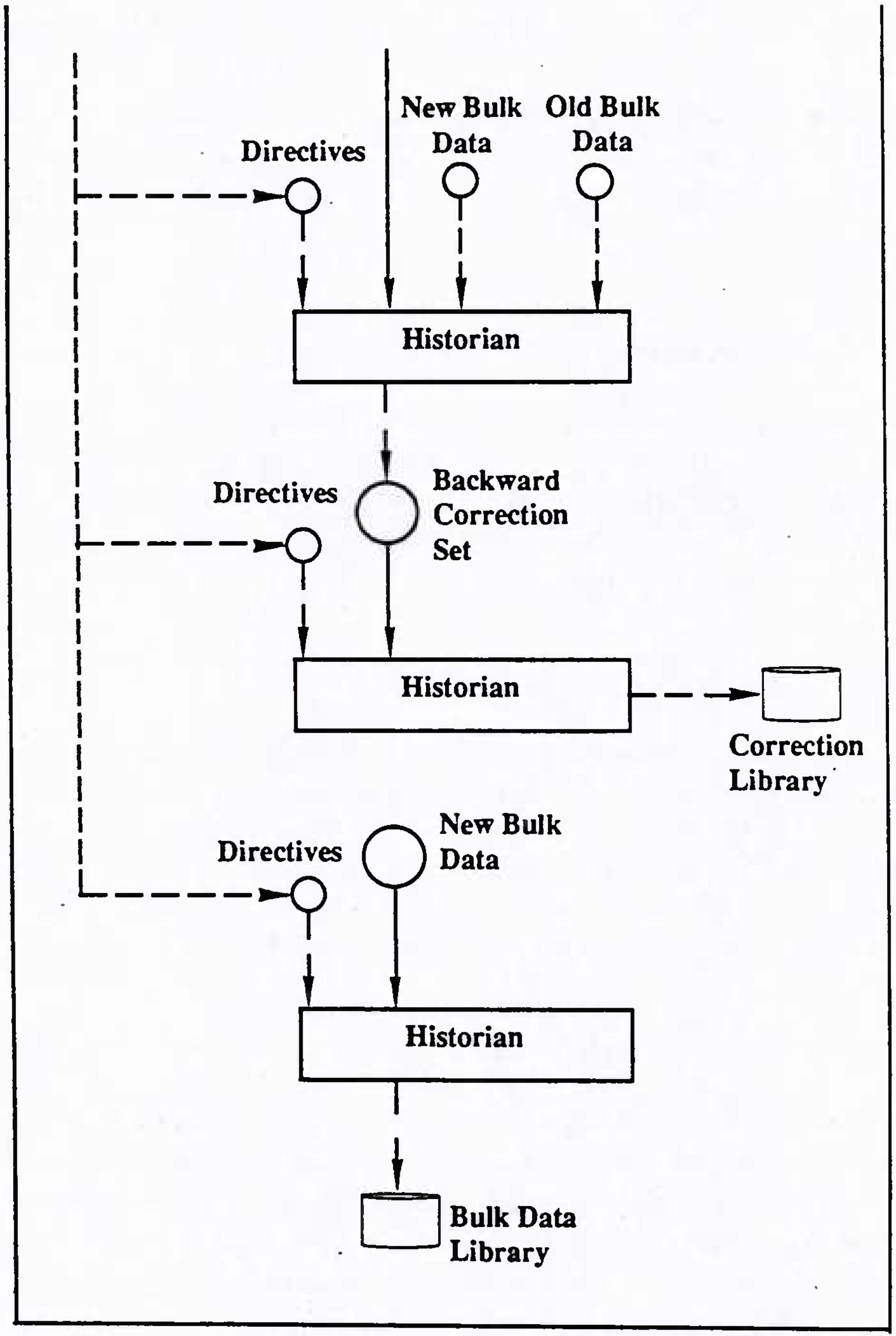

Figure 12. Making a correction (Continued)

new data items to those listed above.

Some unresolved issues remain in this plan. For example, when bulk data descriptions are entered, it would be desirable to ensure that the referenced card(s) actually exist. Also, when changes are made, it would be desirable to delete descriptions of cards that are deleted. These issues could easily be handled by some auxiliary software that could be invoked by the command files generated by FEMREC.

Also, we have not said whether executive control and case control decks would be stored, and if so, whether they would be attached to bulk data decks or stored separately. Arguments can be made either way. This issue will be addressed in Phase II.

7.8 Other Database Approaches

There are of course other solutions to the problems addressed in this section. We briefly mention three of them along with the reasons why the first two were considered unsatisfactory. Again, these decisions are subject to revision if new information becomes available in Phase II. Insufficient information is available at this time to pass judgement on the third option, CDMS.

7.8.1 Other Commercial Database Products

First, many commercial database products are available that do an excellent job with certain kinds of information. However, these products are not generally well suited for large ASCII text files, which is what a bulk data deck is, in essence. The UPDATE/HISTORIAN approach, although based on 20-year-old technology, still provides the best solution, when augmented by a database code such as DATATRIEVE and a driver code which we call FEMREC.

7.8.2 MacNeal-Schwendler's New Database

Second, MacNeal-Schwendler Corporation is making a considerable investment in a new executive system and a new internal database for MSC/NASTRAN. This database will replace the database which was introduced along with superelements about 10 years ago. The new database comes with a data definition language that sophisticated users can use to define relations among data items down to the level of individual fields on bulk data cards. Initially, the main use for this database scheme will be to provide efficient restarts. But the generality of the MSC approach suggests the tempting possibility of using it to document models. However, the MSC database includes several drawbacks for our purposes. First, it is a proprietary

product. Second, it will probably not be released before the end of 1988. Third, information available at present is somewhat sketchy, making it difficult to make projections about using it.

7.8.3 Configuration Data Management System

A system called the Configuration Data Management System (Ref. [7]) has been developed for the Aeromechanics Branch of FDL. This system performs data management, pre-processing, and post-processing functions for users of ten different aerodynamics codes. Users of CDMS may generate geometric models, create input files for any of the codes, initiate execution of a code, retrieve and manipulate output, and pass data downstream to other codes. All this is handled by an executive driven by commands or menu picks. The potential for applying a modified version of CDMS (or a system patterned after CDMS) to finite element analysis is intriguing.

The geometry processor in CDMS is called I3G. It performs six major functions: surface manipulation, surface grid-point generation, display functions, database operations, and output functions. The surface generation functions are kept simple in recognition of the fact that CAD systems do this better. Instead, an interface is provided to access CAD data. I3G requires geometric data in IGES format. Interface codes have been written to convert data from several geometry sources which do not use IGES format.

It should be recognized that the geometric data required for aerodynamic analysis is somewhat different from the geometric data required for finite element analysis. Aerodynamic analysis is concerned solely with surfaces, whereas finite element structural analysis is concerned with line elements, surface elements, and solid regions. Even if we focus attention solely on surface elements, we find details such as stiffeners and cutouts that do not appear in aerodynamic analysis. There is also data like thicknesses and material properties that has no direct parallel in aerodynamic analysis.

It certainly ought to be possible to modify I3G to handle finite element data. However, such an effort would likely end up reinventing the finite element mesh generator, and there are already enough of those around. It thus appears that I3G or an extension thereof would not be suitable for finite element data. This conclusion is based on a review of the CDMS final report (Ref. [7]) which does not go into detail about data formats. Further investigation in Phase II could conceivably reverse this conclusion.

The job submittal and output retrieval functions of CDMS do not seem particularly attractive for finite element programs either. Only one or two analysis programs (NASTRAN and possibly ASTROS) would be used by users of the

proposed database, and procedures for running these codes, interfacing them to pre- and post-processors, etc., are already well developed.

This leaves the possibility of using CDMS' data management facility. Not enough is said about the details of this facility in the Final Report to draw a conclusion. The usefulness of the CDMS/Oracle approach would depend largely on the ability to tailor it to the specific needs of finite element analysis, and on its ability to store supporting documentation along with the data itself. Oracle is a very expensive commercial product. It would likely not be cost-effective to procure a separate Oracle license for the Model Center; an existing installation would have to be used instead.

In short, CDMS does not presently seem attractive for storage and manipulation of finite element data. Again, this conclusion is based on a cursory understanding gained from the Final Report and is subject to review in phase II.

7.8.4 Other Database Software

One other database possibilities is CADDB, the database that accompanies the CADS graphics software. An advantage of this approach is its availability within FDL. CADDB would have to be modified to provide a means for storing identifying information. This possibility will be investigated. Another candidate is RIM, which is available on the FDL VAX, with a smaller version available on PC's. Again the question is whether RIM would be suitable for storing identifying information.

8. Models with Varying Degrees of Refinement

The statement of work includes the sentence, "The study would also address problems associated with different models of the same system that have varying degrees of refinement." This section discusses these problems from several points of view. First is a discussion of how one compares results from such models, for both dynamic and static cases. This is followed by a section on convergence of results as models are refined, and the practice of "smearing." There are discussions of three related topics: reduced-order modeling, model tuning, and meta-models.

The intent of this section is simply to review these topics, pointing out directions that could be followed in a further investigation of this topic.

8.1 Equivalence of Dynamic Models

Dynamic models require much less detail than static models as a rule, because static stresses require local modeling accuracy whereas natural frequencies and modes shapes are generally properties of the structure as a whole, and are only mildly sensitive to local modeling detail. Natural frequencies are the easiest result to check when comparing two models having different degrees of refinement. These numbers can be misleading, however, unless the analyst can assure himself that they represent the same mode shape. Mode shapes may be compared in terms of node points that appear in both models. Mode shapes from both models may be reduced to this set of node points for the comparison. Qualitative comparisons can be made by means of graphical displays (preferably animated).

Assuming such displays have given evidence that the mode shapes appear roughly similar, a numerical evaluation can be made by computing the normalized scalar product of the two mode shapes. A value close to unity indicates good comparison. A more elaborate check involves the computation of revised pseudo-modal mass matrices, i.e., $\mathbf{\Phi}^T\mathbf{M}\mathbf{\Phi}'$, where $\mathbf{\Phi}$ and $\mathbf{\Phi}'$ are the mode shapes being compared, and $\mathbf{M}$ is the mass matrix, reduced to the comparison degrees of freedom. This calculation provides cross-orthogonality checks as well.

These methods also apply to comparison of analytical results to test results.

8.2 Equivalence of Static Models

Static models are generally intended for stress predictions. However, in some cases analysts may be concerned only with static displacements. Displacements, like mode shapes, are less sensitive to local details as a rule, so that coarse models may be compared with fine models much the same as in dynamic cases.

Where stresses are of interest, analysts generally need as much refinement as

they can afford. However, there is one way in which coarse models can be used to advantage in stress analysis. Assume that attention is to be focused on stresses in a particular area of the structure. One can start with a coarse model and compute static deformations and node-point forces. Then, the area of interest can be isolated and modeled in detail. Two approaches are possible: one can either prescribe the displacements from the coarse model on the boundaries of the fine model, or prescribe the node-point forces on the boundary, leaving the displacements free. For statically determinate structures, the latter method is exact and the former method is poor. For a structure having stiff load paths parallel to the section being modeled, prescribed displacements may be more accurate. Since neither extreme case generally holds in practice, either method must be used with some caution. In using such an approach in an optimization study, for example, it would be wise to rerun the coarse model periodically, using the revised properties. A new set of boundary forces or displacements would then be obtained for application to the fine local model. These issues are discussed in some detail in Ref. [8], which presents a combined method in addition to the force and displacement methods.

8.3 Convergence with Mesh Refinement

University courses in finite element analysis, if they discuss theory in any depth at all, treat the problem of convergence of finite element models. The issue is usually discussed in the context of a simple model like a flat plate. A theorem is proven which states something like the following:

> If the model is refined in a systematic way (such that each refinement includes all the node points of its predecessor), and if the finite elements satisfy the conditions of completeness and continuity, then the approximate solution produced by the model approaches the exact solution in the limit as the mesh density increases without bound. For elements formulated with displacements as independent variables, the convergence is monotonic from the stiff side.

The theorem may be illustrated by actually running models with increasing refinement.

The student may come away with a great deal of concern for questions of convergence and accuracy. However, if he begins applying finite element methods in industry, he finds little or no opportunity to deal with such questions. For one thing, such concerns tend to be crowded out by schedule and budget problems. Also, real structures are usually complicated by cutouts, thickness changes, stiffeners, attachments, etc. The analyst's "budget" may be used up just in placing node points at all the corners, thickness changes, etc. This leaves no opportunity for experimenting with refinement of the mesh.

8.4 Smearing

In some cases, parts of structures are so complex that the "budget" of node points would be exceeded if all the details were modeled with distinct elements. In this case, "smearing" is a common technique by which equivalent simple elements are used to model a geometrically complex portion of a structure. For example, a stiffened plate may be modeled by an equivalent homogeneous plate having orthotropic material properties. If properly devised, an equivalent model provides the same stiffness and inertia properties as a refined model, in the modes of deformation which are important for the particular loading being applied.

In practice, however, smearing is generally done with simple rules of thumb which may or may not provide good results. For example, when a uniform plate is used to represent a plate with a hole, one could just average the thickness over the area of the plate. But if the plate vibrates in its first mode, and if the uniform plate predicts that much of the strain energy for that mode is in the area where the hole is, then this "equivalent" plate may in fact be much too stiff.

8.5 Model Tuning

Model tuning refers to the systematic adjustment of selected parameters in a finite element model in order to bring the model into closer agreement with reference values which are considered correct. Usually, these reference values are laboratory test results. The premise is that some of the model parameters, such as joint stiffnesses or bearing stiffnesses, are uncertain, and that by matching selected test results, better values can be obtained for these uncertain parameters. This process may be carried out by optimization software such as ADS/NASOPT or ASTROS.

Suppose, for example, one wanted to tune the first three frequencies to match test data. Then the following optimization problem could be posed:

$$\begin{array}{rl} \text{Minimize} & W(X) \\ \text{subject to} & 0.98\omega_i^T \le \omega_i \le 1.02\omega_i^T \ , \quad i = 1 \ldots 3 \end{array}$$

where ω_i is the i^{th} natural frequency, and ω_i^T is the corresponding test value. X is a vector of "design variables" (in this case, the uncertain model parameters) and $W(X)$ is a dummy objective function. The objective function is immaterial because the initial design would be "infeasible," i.e., the constraints would be violated. The optimizer would ignore the objective function until it was able to find a "feasible" design, i.e., one for which all three computed natural frequencies are within 2% of the corresponding test values. At this point the optimization would be terminated.

The same procedure could be applied in reduced-order modeling. That is, assume a complex model of a given structure exists, and the goal is to create a

simpler model which matches the complex model in certain respects. That is, one might wish to reproduce the first few natural frequencies closely, or predict the same general displacements under a given load.[3] The coarse model could then be run for a few cycles through an optimizer in order to refine its element properties.

8.6 Reduced-order Modeling

The subject of reduced-order modeling is related to the topic at hand. Reduced-order modeling refers to the systematic generation of simplified models of structural systems, and is usually addressed in the context of analysis and design of structures having feedback control devices. For example, Lamberson in Ref. [9] develops a plate finite element to represent complex truss lattices and compares both the static deformations and dynamic mode shapes. He further shows that feedback controllers designed using the simplified model perform as well as those designed with detailed truss models. References [10] and [11] describe similar studies, while Ref. [12] discusses a reduced-order model used in an optimization study.

8.7 Meta-models

Pre-processing codes for finite element programs have existed for many years. Most of these are graphics-oriented. As a rule, models may be generated either by specifying individual grids and elements or by defining regions ("patches," "grids"), and having the software fill in the regions with meshes of a specified density. The definition of a model in terms of these regions may be called a "meta-model."

An example of this process may be seen in Figure 13. In the upper left-hand corner is a plot of a meta-model for a simple piece of structure, having an offset hole and surrounding stiffeners. This meta-model was generated by a GIFTS command file of about twenty lines. By simple modifications to this file, models of varying degrees of fineness may be generated, as seen in the other plots.

Currently many finite element models are generated using pre-processors such as PATRAN or GIFTS, or via interfaces from CAD/CAM programs. Unfortunately none of these methods can be called an industry standard. Thus it does not seem reasonable to include a standard meta-model format in the proposed military specification (Section 6). However, there is no reason why meta-models should not be delivered, even if they are only stored and never exercised by the proposed Center.

[3] One could not expect to reproduce stresses well, however, since these depend so strongly on local modeling details.

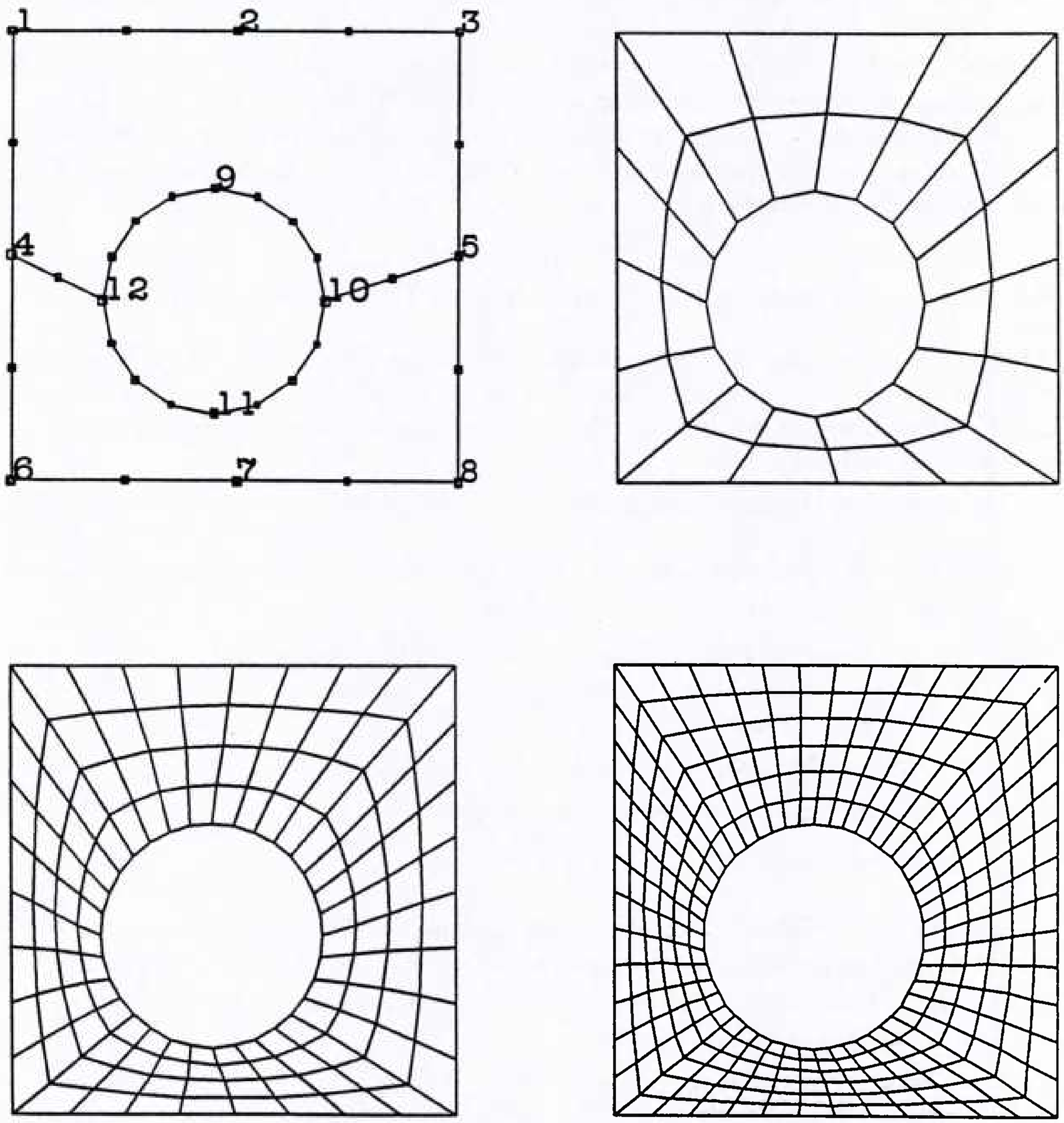

Figure 13. Generating models of various densities from a meta-model

9. Relationship to Other Programs

Two major Air Force logistics programs are presently investigating the integration of design, manufacturing, and logistics data. These programs involve the management of large amounts of technical data, and include the potential for using and transmitting finite element models on a broad scale. During Phase II, progress on these programs will be monitored to see how they might impact a finite element model center, both in the short and long term. It is possible that a synergistic relationship can be established.

9.1 Computer-aided Aquisition and Logistics Support

CALS (Computer-aided Aquisition and Logistics Support) is primarily concerned with the repair and maintenance (R&M) functions of the Air Force Logistics Command. These functions involve some data that is either directly or indirectly related to structural analysis.

The broad goals of the program are:

- Bridge "islands of automation" in DoD and industry design and logistics processes.
- Gain the benefits of a highly automated and integrated system
  - Reduce paper
  - Improve the timeliness and accuracy of information
  - Design more supportable weapons systems
  - Reduce costs

A wide variety of data is expected to be encompassed by CALS, including technical publications such as standards and technical manuals, engineering drawings, and CAD/CAE databases. No specific mention of finite element models has been found in CALS publications, however.

The specified functional requirements of the system are

- Development of an integrated design, manufacturing, and logistics database to provide
  - Near real-time configuration updates
  - Specified government access
  - Database transportability

- Use of online R&M design tools in a CAD/CAE integrated environment
- Automated generation of logistics data products such as tech manuals and engineering drawings.

9.2 Integrated Design Support System

IDS (Integrated Design Support System) is designed to provide direct engineering support for maintenance, modification, and repair of Air Force Weapons systems. The IDS goal is to develop a computer software system to manage technical data across the life cycle of a system. IDS is similar to CALS in requiring the capture of data from design, manufacturing, and logistics. It differs in scope (Air Force only), and in the emphasis of the program. IDS is more technically oriented, with data ranging from engineering drawings through structural and aerodynamic analysis data, to process plans and fabrication techniques, and concludes with tech order maintenance and repair data.

As an integral part of IDS, it is envisioned that finite element models will be available from contractors on call and can be transmitted electronically when needed for analysis. While model delivery is still in the future, this aspect of IDS will be monitored closely, since it bears directly on the mission of the proposed Model Center.

10. Phase II Operation

This section outlines plans for Phase II of this SBIR. The formal Phase II proposal appears in a separate document.

Basically, three overlapping efforts are foreseen: (1) identification, acquisition and development of software and computer hardware; (2) exercise of the software and procedures on one or more full-scale finite element models, and (3) preparation for full-time operation of the Air Force Aircraft Model Center.

10.1 Software Identification, Acquisition, and Development

Section 7 recommended a software solution tailored to the needs of finite element users. It also listed alternatives which appear less favorable. The first task in Phase II will be to review the alternatives. Alternative packages will be tried out on a computer, if possible, and more detailed information on the advantages and disadvantages of each will be developed, along with hardware requirements and cost estimates. The approach recommended in Section 7 consists of two commercial components: DATATRIEVE (currently available on the FDL VAX), and HISTORIAN (which would have to be procured). Driver code called FEMREC would have to be written. This would be a modest effort since similar driver code has already been written by Mr. Tenorio of ATA. A decision on whether to pursue this approach or an alternative will be reached, subject to review by the Air Force Project Engineer. This decision should be made within one month after start of work, so that procurement of any required software can proceed promptly.

There will be other software needs, besides the basic database software, some of which can be listed here, and some which will become apparent as Phase II proceeds. First, CSA has some existing software that will be contributed. These are ancillary programs for finite elements, including RATS (element quality checks), NASTIDY (renumbering), and NASSET (set generation). MSET (modal strain energy tabulation) will also be contributed. Another auxiliary code that would be useful would read existing comments from a bulk data deck and format them for insertion in the database. (See the discussion of descriptor files in Section 7.)

Access to the VAX computers at FDL will have to be arranged, along with computer time for running NASTRAN on the Cyber or Cray mainframes.

10.2 Work with a Large-scale Model

After the required software has been procured and/or developed, and methods for its use established, it will first be checked out on a small model, sufficient to work out bugs or shortcomings from the software. Soon thereafter, work will begin on an

existing detailed model of an Air Force aircraft. The F-15 C/D model appears to be a good candidate for this activity, but the actual choice will be made with the cooperation of the Air Force project engineer. In addition to the model itself, we will attempt to acquire as much supporting documentation as possible, especially contractor stress reports and drawings. The selected model will first be assessed as received as to completeness, documentation, reliability, and range of applicability. This will involve a number of NASTRAN runs.

After the model has been verified, it will be entered into the database. This will involve entering descriptive information as well as the actual bulk data. After that, variations will be generated and documented using the database.

10.3 Preparation for Full-Time Operation of the Center

The work described in the previous paragraphs will provide a valuable end product in itself. That is, the F-15 data and the database software would be available for the needs of FDL or other organizations. In addition, a major goal of Phase II will be preparation for subsequent permanent operation of the Center. One key to reaching this goal will be involvement of Air Force people in Phase II. This is because the Center is envisioned as a service organization, and involvement of future customers during Phase II will help insure the success of the Center after it begins operation.

Once the software and procedures have become operational, it is hoped that the Air Force project engineer and/or other interested Air Force engineers will become involved directly in exercising the software, generating variations of models, recommending changes in procedures, etc. Also, after the database has been populated with the basic model and several variations, another useful exercise can be undertaken. An Air Force engineer will be invited to use the database system with minimal coaching from the contractor. Besides examining the database and extracting data, this engineer should be encouraged to make modifications and new entries. This will provide valuable feedback to the contractors.

It would also be wise to solicit the attention of the SPO's and other ASD organizations during Phase II. This would be especially true of ASD/ENFS, which has already expressed interest in the Center.

10.4 Division of Work

Work will be divided among three sites: CSA's offices in Palo Alto, CA; ATA's offices in Albuquerque, NM; and the Flight Dynamics Laboratory (preferably Building 45). All three sites are equipped with VAX computers which can exchange data files over telephone lines using Kermit. All three organizations have IBM-compatible personal computers, in the event that software for these computers is selected.

CSA will be the prime contractor, and will do all the administrative work and some of the technical work at its offices. The technical work will include some NASTRAN runs on CSA's VAX, and some work with the database software and the selected models. If the HISTORIAN/DATATRIEVE approach is selected, CSA will procure DATATRIEVE and HISTORIAN for its VAX.

ATA will do initial software development and integration at its offices. CSA will exercise the software on the ATA VAX via a telephone connection. It will then be installed on the CSA and FDL VAXes and exercised there. Of course, any necessary procurement would have to be completed beforehand.

Aerospace Structures, Inc., will have primary responsibility for the work done at FDL, and may also do some work off-base. This will include acquisition of the selected model or models, and supporting documentation. Aerospace Structures will maintain close contact with Air Force personnel on technical matters. It is hoped that these contacts will be maintained almost daily once the software is ready and the models are in hand.

11. Operation of the Air Force Aircraft Model Center

This section is a preliminary look ahead to permanent operation of the proposed Air Force Aircraft Model Center. As experience is gained in Phase II, these ideas may of course be greatly expanded or modified.

This entire report has emphasized the need for an Air Force Aircraft Model Center. To reiterate, the Air Force is not getting full value for the resources that are expended on finite element models. Contractors should be required to deliver models to the Air Force. These models (and others that are available to the Air Force) should be documented, exercised, verified, and publicized by the Center. The Center would then stand ready to provide Air Force organizations or contractors with models, and could assist in modifying these models as needed.

It should be emphasized that the Center is not envisioned simply as a repository or a library function. The Center would provide engineering expertise and a "corporate memory" of the models it stores that would encompass drawings, reports, and other information in addition to the computerized database.

To some degree, Phase II will be a trial operation of the Center. A physical presence on the base is anticipated, with close cooperation with Air Force engineers on technical matters. While the doors will not be open for business in the sense of a fully functioning Center, it is expected that Phase II will gain visibility and interest among Air Force engineers so that the Center could begin operations with an initial customer base in addition to the necessary technical capability. Presentations at meetings such as ASIP would also help publicize the future Center.

A key word in the operation of the Center must be *service*. The staff must understand the position of an engineer who needs a finite element model and is under pressure from budget and schedule constraints. While the customer would likely phrase his request in specific terms, the Center engineer should solicit more information about the underlying requirement, to be sure that the customer is asking the right question. Few if any problems would be solved by simple delivery of a tape, with no further interaction.

Quality will be another key to success. An engineer under pressure must be able to count on the quality of the data he receives from the Center. This means special emphasis on verification of models and on documenting their limitations.

Two more key words (which may seem to contradict each other) are *publicity* and *security*. As a service organization, the Center's success will depend largely on its ability to publicize its existence and the models it has to offer among potential customers. On the other hand, the models that are stored are valuable, and must not be delivered to unauthorized parties. One of the most attractive features of

the HISTORIAN/DATATRIEVE approach recommended in Section 7. is the fact that information is stored in one set of files and the actual data in another. This makes it possible to store the actual data in a secure manner (off-line, for example) while making the information files freely available to customers who wish to browse through the database contents.

Mr. Negaard of Aerospace Structures, Inc., and Dr. Johnson of CSA are both former managers of ASIAC. They understand the operations of a service organization and are well qualified to guide the Air Force Aircraft Model Center through its crucial initial years of operation.

As a minimum, the Center would be staffed part-time by a senior engineer and full-time by a junior engineer with good computer skills and some finite element background. A MicroVAX or equivalent engineering workstation would probably be required.

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Appendix A: Interview Transcripts

This appendix presents interviews that were conducted with six Air Force organizations and one NASA organization. The following organizations were surveyed: ASD/ENFS (WPAFB), Eglin AFB, 4950th Test Wing (WPAFB), Warner-Robbins ALC, Hill AFB, Sacramento ALC (McClellan AFB), and NASA/Dryden. One transcript is provided for each organization, following a standard format.

A.1 ASD/ENFS, WPAFB

Interviewer: G. Negaard (in person)

Persons interviewed: Hugh Griffis, Robert Moore

Organizational mission:

Review contractors' structural analysis including finite element analysis. Perform hardness assessments, look at flutter problems.

Organizational capability:

Personnel: Two people in the vulnerability group, three in the flutter group. Other ASD structures personnel are scattered among the SPO's.

Expertise: Novice to intermediate, able to understand contractors' work and perform some FE analysis.

Equipment: CDC and VAX, Tektronix terminals; PATRAN, NASTRAN. They have developed the DATANET code which uses FASTGEN, MOVIE.BYU, and TRACELINKS to do animation of large models. They are getting NAVGRAF (a new package which encompasses graphic pre-processing, COSMIC NASTRAN, and graphic post-processing). They are having a ballistics and laser vulnerability capability put into ASTROS.

Organizational use of finite element models:

They review contractors' analysis, check some of it.

Use NASTRAN and thermal codes. Perform 1-D thermal analysis to check for exceeding elastic limits. Panel analysis for overpressures.

Did T-46 flutter analysis using NASTRAN to get natural frequencies and modes shapes, then FACES for flutter analysis.

Acquisition methods:

How are models obtained?

Via S.O.W. where possible, otherwise by "begging, borrowing, or stealing".

How are such models verified and understood?

By contractors only, to any real degree.

How are they archived and retrieved?

Not really archived at all.

Lessons learned in this area?

Need a system to obtain and keep models.

Existing or potential needs for FE models:

F-15E model coming. Will be in McDonnell-Douglas format, will have to be converted to NASTRAN.

Have an F-15C/D model in McDonnell-Douglas format, with numerous errors.

Have a need for the dual role fighter model (F-16E?)

HALE (High Altitude Long Endurance) aircraft coming up

Awareness of FE models developed by contractors:

GLCM (Ground-Launched Cruise Missile). Launcher, truck, and trailer.

B-52 (on paper ... needs tying in)

KC-135 (on paper ... needs tying in)

Response to the idea of a model center:

They favor the idea, suggest that AFWAL draft a letter to each Program Office asking them for a model with necessary documentation.

How they would like to see a Model Center work:

They would like someone to take paper listing of models, put them up, verify, and make them available as needed.

There is no real need for quick response. A few days or weeks is quick enough for their needs.

Estimate of funds or time that might be saved if a Model Center existed:

Paraphrasing: "When you have to go to the contractor for a model, it's going to take a year or more, so if something has to be done in a timely manner, it doesn't get done. Having a model available would allow analysis of problems that often are not attempted due to time constraints."

As for funds, the F-15C/D model was obtained for $50,000 from the contractor. This procurement was tacked on to a larger contract. The model was actually "free"; it was the documentation that cost $50,000. However, if the contractor were asked to create a model it would cost at least $500,000.

A.2 Eglin AFB

Interviewer: G. Negaard (telephone)

Persons interviewed: Jim Robinson, Wayne Ingraham

Phone number: AV 88-872-2748/3017

Organizational Mission:

Store certification for aircraft and stores.

Organizational capability:

Personnel: Three people in flutter analysis, three in loads.

Expertise: Mostly in flutter. Loads people have two entry level engineers, one more experienced analyst.

Equipment: Cyber 176 mainframe, MSC/NASTRAN only.

Organizational use of finite element models:

To analyze flutter with stores.

Acquisition methods:

How are models obtained?

They have usually gone to contractors for models. They do not do any modeling of their own. They typically use stick models for dynamic analysis.

How are such models verified and understood?

Apply allowable loads. If wing torsion or wing bending exceed allowable limits at any station, they go back to the contractor for additional analysis.

How are they archived and retrieved?

They have no system.

Existing or potential needs for FE models:

F-111 (future)

A-10, F-4 flutter models

F-15 A/B/C/D models (now on hand)

Getting F-16 model from GD in a month – primarily wing, fuselage and empennage represented by gross elements. The model will have 100-200 elements for dynamic analysis.

Awareness of FE models developed by contractors:

F-15 models

F-16 model

Response to the idea of a model center:

No response; not knowledgeable.

Estimate of funds or time that might be saved if a Model Center existed:

They had no idea but felt they could benefit.

A.3 4950th Test Wing

Interviewer: G. Negaard (in person)

Persons interviewed: Lloyd Matson, George Perley

Organizational Mission:

Design and build modifications to existing aircraft. They are presently converting several old commercial 707's to C-18's.

Organizational capability:

Personnel: Ten people

Expertise: Static, dynamic, and flutter analysis. Considerable expertise, ranging from a few years to ten or more.

Equipment: Cray, CDC, and VAX, Tektronix terminals; PATRAN, NASTRAN. Access to MSC/NASTRAN via Cybernet. One Evans & Sutherland graphics system. They have three VAXes of their own, and four or five MicroVAXes. They are going out for a CAD/CAM/ CAE system – Sun, Apollo, or Intergraph.

Organizational use of finite element models:

Usually to check static strength for aircraft modifications such as radomes or equipment racks. They are also working on a project called ECCM/ARTB (Electronic Countermeasures/Advanced Radar Test Bed) which requires cutting holes in the top of a C-141 fuselage to mount radomes.

Acquisition methods:

How are models obtained?

They often build their own models but sometimes go out on contract. Rockwell, for example, just made them a model of a 450-inch fuselage section of a C-141.

How are such models verified and understood?

By comparing to existing models or similar data. Also with hand calculations. For example, the Rockwell C-141 fuselage model showed negative margins of safety in several places, and the original Lockheed analysis did

not. However, these points are places where the C-141 has had fatigue problems, which helped verify the Rockwell model.

How are they archived and retrieved?

Cards, tape, hard-copy printout. No system for permanent storage.

Lessons learned in this area?

They need a system to catalog and keep track of models.

Existing or potential needs for FE models:

C-18 (Boeing 707) fuselage to aid in fatigue analysis

C-135

C-141

T-39

A-37

A-7D

Awareness of FE models developed by contractors:

C-141 done by Rockwell

Response to the idea of a model center:

They favor the idea, if the procedure can be quick and painless.

How they would like to see a Model Center work:

They would like to be able to pick up the phone, interrogate a database, pull up a pictures of models, then order the components decided upon.

Estimate of funds or time that might be saved if a Model Center existed:

They have no idea, because their needs are so special that they generally have to start from scratch and build their own models. (Note: the 4950th was unaware of the C-141 COSMIC NASTRAN model that Warner-Robbins has. We gave them a contact to call there.)

A.4 Warner-Robbins ALC

Interviewer: G. Negaard (telephone)

Persons interviewed: Robert Wade, Lt Randy Jansen

Phone number: AV 88-468-2525

Organizational Mission:

Depot maintenance for C-141, C-130, F-15, and H-53 aircraft.

Organizational capability:

Personnel: Seven engineers and a manager.

Expertise: Mostly static analysis.

Equipment: Dedicated VAX-11/785, Tektronix terminals, MSC/NASTRAN, Supertab.

Organizational use of finite element models:

Usually to check static strength for aircraft modifications or repairs. They use large models to get internal loads which are then used for stress analysis on small parts. They also look at fatigue problems.

Acquisition methods:

How are models obtained?

They usually build the component models they need.

How are such models verified and understood?

"As best one can." Hand calculations, for example.

How are they archived and retrieved?

On tapes and on the VAX.

Existing or potential needs for FE models:

They have C-130 and C-141 COSMIC NASTRAN models.

They are getting an F-15E model in MacAir format; need to convert it to NASTRAN.

Awareness of FE models developed by contractors:

F-15 Models

Response to the idea of a model center:

Not much need for large models except to get loads for components. For small models, they go straight to the drawings, work off the drawings as needed, or take measurements from parts.

How they would like to see a Model Center work:

Moderate interest, not sure how they would benefit.

Estimate of funds or time that might be saved if a Model Center existed:

No idea.

A.5 Hill AFB (MMSR, MMAR, MMMDR, MMIR)

Interviewer: M. James (in person)

Persons interviewed: Bret Hamblin, Tim Sorensen, Bruce Burgon

Phone number: (801) 777-7072

Organizational Mission:

Perform fatigue analysis on various parts of the F-4 and F-16 aircraft. Hill AFB is the central depository for all aircraft landing gear technology throughout the Air Force.

Organizational capability:

Personnel: MMSR: 8 civilian, 3 military; MMAR: 10 civilian, 2 military; MMMDR: 4 civilian, 1 military

Expertise: Novices in the use of both NASTRAN and CRACKS 85. The longest experience of any individual is two years. Contractors supply the necessary expertise, as a rule.

Equipment: Two clustered VAX-11/785's, Tektronix 4109 and 4129 terminals.

Organizational use of finite element models:

They develop finite element models for fatigue analysis, primarily, but also do some design and repair work. The models are usually created in-house with some assistance from contractors (BYU and General Dynamics), or by outright purchase (F-16 from General Dynamics).

Acquisition methods:

How are models obtained?

Purchased from manufacturer or created in-house.

How are such models verified and understood?

No verification yet!

How are they archived and retrieved?

Models are stored on VAX disks and backed up on magnetic tape.

Lessons learned in this area?

Disk crashes have resulted in a loss of time and effort. No crash has been bad enough to endanger the models totally but a few days' worth of work was lost at times!

Existing or potential needs for FE models:

F-16 and F-4 aircraft for fatigue analysis. Hill AFB is the depository for all aircraft landing gear, including models.

Awareness of FE models developed by contractors:

MacAir has an F-4 model.

General Dynamics has a complete model of the F-16. (They are rumored to have an F-16E model as well.)

Response to the idea of a model center:

They are very receptive. They do express a concern that the repository may get tangled in the typical government red tape, however. It must be run by contractors and it must be "user-friendly."

How they would like to see a Model Center work:

A pictorial display of the model using an MSC/NASTRAN database of superelements of the entire aircraft. All models must be completely verified to be worth while!

Estimate of funds or time that might be saved if a Model Center existed:

A lot of money may be saved by ensuring that all models being used throughout the Air Force are keyed to the current revision of the aircraft. The other armed services should be consulted regarding models they have so as to reduce redundant efforts in model building and verification.

A.6 Sacramento ALC

Interviewer: W. Gibson (in person)

Persons interviewed: Mr. Sal Alestra

Phone number: (916) 643-5300

Organizational Mission:

F-111 and A-10 aircraft. Mostly stress analysis with concentration on durability and damage tolerance assessments.

Organizational capability:

Personnel: Five engineers and a manager.

Expertise: Mostly static analysis.

Equipment: VAX-11/780. MSC/NASTRAN, GIFTS.

Organizational use of finite element models:

They use F-111 and A-10 models primarily for analysis of damage and corrosion. However, due to manpower problems, they are largely in a reactive mode.

Acquisition methods:

How are models obtained?

They "found" three A-10 models.

Are paying for two F-111 models; will procure six more.

Model deliver will be a future contractual requirement.

How are such models verified and understood?

GD provides them with GIFTS steering files. They use GIFTS interactive viewing commands to gain understanding of models.

How are they archived and retrieved?

On the VAX, with backup tapes.

Existing or potential needs for FE models:

They are getting new F-111 models from GD.

Awareness of FE models developed by contractors:

Strong awareness of F-111 and A-10 models developed by GD

Response to the idea of a model center:

They do not favor the idea. They say they are they only Air Force organization doing analysis on the F-111 aircraft.[4] Therefore they should be in charge of all F-111 models. They see requirements for them to send models to the Center as an additional burden that would detract from their main mission.

How they would like to see a Model Center work:

Use of COSMIC NASTRAN instead of MSC/NASTRAN would be a "kiss of death" for the Center.

A.7 NASA/Dryden

Interviewer: M. James (telephone)

Persons interviewed: Alan Carter, Larry Shuster

Phone Number: (805) 258-3311 ext 3919

[4] However, Warner-Robbins personnel expressed an interest in an F-111 model. See Section A.4.

Organizational Mission:

Maintain finite element models of aircraft at NASA/Dryden and update those models when changes occur to either the structure and the stores.

Organizational Capability:

Expertise: Several experts in the field of structural analysis using codes such as COSMIC and MSC/NASTRAN.

Equipment: VAX's and an ELXI multiple processor system.

Organizational use of finite element models:

On-site development of finite element models to be used for stress, dynamic and loads analysis. Most models are made in-house but a few have been procured from contractors.

Acquisition Method:

How are models obtained?

Made in-house usually.

How are such models verified and understood?

In-house models are verified as they are made. The modeler must trust the drawings and other items used to make models. The understanding of the models is very great because the author of the model is at NASA/Dryden.

How are they archived and retrieved?

The models are constructed and placed in storage on the computer system. Paper writeups are available to identify models.

Lessons learned in this area?

The models must be backed up on computer tape to ensure that they are secure from loss. No problems otherwise.

Existing or potential needs for FE models:

NASA/Dryden has models of the B1-A and the X29 forward swept-wing aircraft. They see no need for other models as yet but as aircraft are added to the inventory at Dryden they will either acquire or build models of those aircraft.

Awareness of FE models developed by contractors:

NASA/Dryden has little contact with outside contractors in the modeling area except for COSMIC NASTRAN colloquia. Rockwell provided the B1-A model at Dryden and should have a B1-B model.

Response to the idea of a model center:

Larry Shuster seemed pleased to hear that a finite element model center is being talked about. He believes that the center would be a major step forward but the problems associated with the center could be great. The major problem will be cooperation from all the organizations involved.

How would they like to see a model center work:

Not sure that they would use the center except to possibly contribute models to the center!

Estimate of funds or time that might be saved if a Model Center existed:

Would not use center for retrieval of models but may participate after acceptance throughout the FEM community.

*U.S. GPO: 648-056/04493/10-19-89/100